LIONFISH DERBY: DYNAMIC OPTIMIZATION MODEL OF A FISHING TOURNAMENT TO CONTROL LOCAL INVASIVE SPECIES

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

By

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August 2017

ABSTRACT

Invasive species have caused significant environmental and economic damage in the United States. Depending on the biology of the invasive species, magnitude of economic damage, and cost of eradication or control, it may be optimal to eliminate (locally extirpate) an invasive species or to limit the population to levels that reduce the economic damage from what it would have been without control. This thesis examines the role that economic incentives might play in controlling an invasive species; specifically, a fishing derby that awards prize money to individuals who remove (harvest) the most lionfish (*Pterois volitans*), an invasive species now widespread in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. The thesis presents a bioeconomic model to simulate the lionfish population when a derby is held if the estimated lionfish population exceeds a management threshold and when optimal prize money is awarded. The model is calibrated to derbies that have been held off Key Largo, Florida. Lionfish derbies require participants to register as members of a team. The team may then use spears or nets to harvest lionfish from coral reefs in a specified (derby-competition) area. Greater prize money will make the derby more ex- pensive to conduct but, in theory, should attract more teams and increase the aggregate level of harvest by those teams that participate but do not win prize money. The data in this thesis come from two sources: (1) biological research on the *ex-ante* and *ex-post* lionfish density in the derby (competition) area, and (2) the aggregate harvest and prize money awarded to the teams achieving the greatest harvested biomass. Simulation and optimization results indicate that derbies can significantly reduce lionfish biomass in a derby area when the population level that triggers a derby is above the steady-state lionfish population if the derby were held *every year*. However, when the population level that triggers a derby is below the steady-state population when derbies are held every year, lionfish biomass will increase back toward an environmental carrying capacity (the maximum population with no harvest). Optimal

prize money, economic damage done by lionfish, and the steady-state lionfish populations are all highly sensitive to carrying capacity. An increase in carrying capacity increases optimal prize money, steady-state lionfish population, and economic damage. Optimal prize money and the economic damage from lionfish are less sensitive to the rate of discount. An increase in the damage parameter, reflecting the marginal damage from lionfish, causes an increase in the optimal prize money and lionfish damage, but reduces the optimal steady-state biomass.

BIOGRAPHICAL SKETCH

Linghui Wu was born in 1992 in Dalian, China. She began her studies in Agriculture and Forestry Management at China Agricultural University in 2010 and transferred to University of Maryland in 2012. While studying in Maryland Department of Agricultural and Resource Economics within the College of Agriculture and Natural Resources, Wu developed an interest in natural resource economics. In 2015 she was admitted to the master program in the Department of Applied Economics at Cornell University, where she has studied dynamic optimization methods to incorporate human behaviors with natural resources, especially in the management of invasive species.

To all the people who have contributed great efforts in invasive species management program. To future generations that it might be a better world for you to experience and enjoy. And to a better relationship with lionfish in the future.

ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my thesis chair, Prof. Jon Conrad, for his continuous support of my graduate study and for his patience, motivation, and immense knowledge. He guided me through all of the research and writing of this thesis. His assistance on communicating with scientific institutions, constructing models, and related research questions gave me very valuable experience in how to conduct research. Most of all I am grateful for his patience and his forgiveness of my naive questions.

I would also like to thank my other committee advisor, Prof. Ariel Oritze-Bobea for his insightful comments and encouragement, and for his hard questions that incentivized me to widen my research to include various perspectives.

My sincere thanks also goes to my program chair, Prof. Calum Turvey, and Dyson School Program Coordinator Mrs. Linda G. Sanderson, who supported me in my studies and made me feel welcome.

I also want to express appreciation for the late Prof. Gregory Poe. Although he was not a member of my committee, his professional dedication inspired me greatly. I was fortunate to have had a long talk with him — not so much about academic study but on accommodating the research life and being a qualified scholar—and I will remember this inspiring conversation all my life because it made me a better person.

Thanks to Mr. Lad Akins and Dr. Stephanie Green for sharing their derby data and research information with me. I am really grateful for their continuous effort in conducting lionfish events and research. Thanks for their detailed explanation of how the lionfish derby proceeds in Key Largo, Florida.

Thank you to my colleagues in Warren Hall for support, encouragement, and invitations for happy hours, barbecues, dinners, and parties.

Last but not the least, I thank my family: My parents have supported me spiritually throughout the writing of this thesis and through my whole life.

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CHAPTER 1

INTRODUCTION

It is now acknowledged that non-indigenous species not only cause environmental damage, they also lead to great economic losses. In the Pimentel (2005) study of alien-invasive species' environmental and economic costs in the United States, annual losses of $120 million resulted from non-indigenous species, and this is a low estimate. In the past it was assumed that only disturbed habitats and communities were likely to be affected; however, conservation studies show that even species-rich habitats can be threatened by non-indigenous species.

There is no general framework of all invasive species in the United States; instead there are various reports on the specific effects of particular species in specific sites. There are also reviews of particular kinds of invasions-by aquatic weeds, agricultural pets, etc. (Simberloff et al., 1997). Management tools are designed for a particular species in a particular area with the understanding that targeting species population dynamics and their interactions with local environments are key factors for management success (Pasko et al., 2014).

1.1 Incentive Programs

Incentive programs—such as bounty programs, contract operations, commercial markets and recreational harvests-are gaining public awareness as means to control or eradicate invasive species. Incentive programs help control the density of invasive species while simultaneously developing a local economy.

Susan Pasko and Jason Goldberg (2014) summarize the biological, ecological, human health, socioeconomic, and other factors involved in successful incentive programs. However, they do not point out whether these incentive programs are effective in their long-term impacts on invasive species. Sustained species monitoring, data recording, and specific program research are all needed for future incentive programs and invasive species management.

1.2 Why Lionfish in Key Largo, Florida

Several features of the state of Florida make it an easy place for species invasion. The peninsula has many new habitats and not many native species that might be easily disturbed by humans. South Florida also has large tropical areas with warm temperatures that allow many species to survive. Studies show that abundant lakes, streams, and other wetland habitats provide great opportunity for aquatic non-native plants and animals to be introduced. Other factors, such as modification of the state's waterways for irrigation, water supplies, flood control, and extensive recreation, has promoted the further spread of non-native species. Approximately 7,800 lakes comprise 6% of Florida's area and 1,700 rivers dissect the state. Last but not least, Florida is a transportation hub and a center of tourism from other regions of the country and the world. Miami is the entry port for most visitors from Latin America and has numerous flights from other regions: 85% of plant shipments pass through Miami and there were 333 million plants in 1990 (Simberloff et al., 1997).

The lionfish is one of most invasive species of fish in Florida. One effort to curb its impact is the lionfish derby, which has been held in Key Largo since

2010 with the support of a non-profit organization, Reef Environmental Education Foundation (REEF). There is sufficient data for studying this derby: the organizers recorded the numbers and sizes of harvested fish, participant numbers, and prize monies awarded. Also, ecological estimation work of lionfish in Florida has been done and that contributes to the construction of the bioeconomic model in this analysis.

1.3 Objectives

This paper constructs a bioeconomic model that combines lionfish population dynamics with derby harvests to assess the effects of derbies in controlling invasive species and how to optimize prize money and determine total costs for a sustainable level of lionfish biomass.

The lionfish population dynamic follows a logistic net growth function and a harvest function and adopts a simple catch-per-unit-effort production function that simplifies participants' fishing efforts as a total number of participating teams.

There are three main questions I seek to answer are these:

(1) Does a derby-designated lionfish threshold $[x^*,\ p^*]$ have control effects on lionfish biomass?

(2) How can invasive-species managers make decisions in choosing appropriately designated lionfish biomass x^* and awarding prizes p^*?

(3) How are optimal prize money, total costs, and sustained lionfish biomass

levels affected by a change in each bioeconomic parameter?

It is hoped that the model constructed in this paper will be taken as a reference for REEF's future lionfish control management as it monitors lionfish, records data, analyzes derby, and makes plans. It is also hoped that managers of other invasive species, and related institutions and governments, can take cues here for constructing their own incentive programs to control invasive species.

1.4 Organization

Chapter 2 reviews the literature on major methods of invasive species management: the four major types of incentive programs and factors to be considered in designing management programs. In addition, some examples of invasive species incentive programs that use tournaments are listed. At the end, some related lionfish derby research is introduced.

Chapter 3 reviews how this thesis's dynamic optimization program is constructed. It first introduces the logistic net growth function of lionfish. Then it adopts the catch-per-unit effort function of the harvest and simplifies lionfish derby participants' fishing behaviors by grouping them into a number of participating teams of four people each. This can be done because all the fishermen in the derby share a similar fishing environment and use similar equipment.

Chapter 4 carefully introduces the lionfish situation in Florida. It describes the derby form, and it introduces research related to data and model parameters in Florida.

Chapter 5 conducts an econometric analysis of lionfish and produces sensitivity analysis of some key parameters, such as environmental carrying capacity (K), discount rate (δ) and environmental damage coefficient (d).

Chapter 6 offers conclusions.

CHAPTER 2

LITERATURE REVIEW

There are approximately 50,000 foreign plant and animal species in the U.S. today and environmental damages caused by some of these species amounts to almost $120 million per year. Incentivizing and encouraging public or commercial harvest can be effective tools in controlling invasive species while helping to protect natural resource, develop the economy, and simultaneously awaken environmental awareness. Invasive-species managers need to consider biological, ecological, human health, and socioeconomic factors to design successful management plans that also anticipate unexpected negative effects, such as the broader spread of invasive species or wasted resources (Pasko et al., 2014). There has been several invasive species control programs using tournaments, including the Burmese Python Challenge in the Everglades, Asian Carp contests along the Illinois River, and Lionfish Derby throughout Florida.

2.1 Invasive Species

2.1.1 Major Invasive Species

Some non-indigenous species have caused great environmental damage and economic losses in agriculture, forestry, and several other segments of the U.S. economy. According to David Pimentel, Rodolfo Zuniga and Doug Morrison (2005), environmental damages and losses add up to almost $120 billion per year, there are 50,000 foreign species in U.S., and approximately 42% of native species are threatened or endangered species are at risk because of competition with or predation by alien-invasive species (Pimentel et al., 2005).

The $120 billion in damages per year is a low estimate. The reason for this is that data on invasive species damage or indirect effects, are not readily available. Pimentel suggests that invasive species costs will definitely rise several times higher than $120 billion per year if we include in our estimate species extinctions and losses in biodiversity, ecosystem services, and aesthetics (Pimentel et al., 2005).

Most invasive fish have been established in mild climates area such as Florida's, where there are an estimated 50 species (Courtenay, 1997). Although sport fishing contributes $69 billion to the U.S. economy (Bjergo et al., 1995; U.S. Bureau of the Census (USBC), 2001), a conservative estimate of the economic losses of non-native fish is $5.4 billion annually from more than 40 alien invasive species (Pimentel et al. 2005).

Pimentel suggests adopting various strategies simultaneously to prevent further damage to ecosystem and environment. For example, public education, sanitation, and effective prevention programs at airports, seaports, and other ports of entry can help reduce the possibilities of biological invaders entering into the United States (Pimentel. et al, 2005).

2.1.2 Major Management Factors

A successful invasive species management plan needs to consider various factors and to find the most viable and appropriate approach. Several major factors need to be evaluated.

Biological Factors

Invasive-species managers need to consider the biological characteristics of targeted species. First, a targeted invasive species' population dynamics need to be fully considered: it is necessary for calculating threshold invasive-species density or required invasive-species reduction in the population (Pasko et al., 2014). An Asian carp commercial harvest, for example, can help explain the importance of population dynamics: Harvest efforts focus on large carp since this size is most desirable for food markets. While this may benefit the ecosystem by reducing average fish size, it decreases the likelihood of effective population control because it ignores most of the smaller juveniles (Garvey et al, 2012; Tsehaye et al, 2013).

Second, lack of consideration of the biological characteristics of targeted species, such as demographic structure and density-dependent processes, may lead to further side effects, called biological overconsumption. In the 2002-2003 Australian Victorian Fox Bounty Trial, approximately 20% of Victoria's red fox population was removed by hunters for pay. This trail actually simulated fox population *growth*: since more resources were available for the surviving 80%, the trail had effectively culled the population, producing a counterproductive effect on population removal (Faithfull et al., 2005).

Third, reinvasion may occur if invasive species dispersal and occupied range is too widespread to eradicate them. For example, in Great Britain nutria was effectively eradicated, but it has been difficult to replicate that success in the United States where the nutria population is much greater and more widespread (Louisiana department of wildlife and fisheries (LWF), 2012a).

Last but not least, estimating a population's size is necessary for any incentive program to check whether program goals have been achieved; this can be challenging because invasive species' physical characteristics and living habitats make them hard to detect (Pasko et al., 2014).

Ecological Factors

In addition to the biological consideration of invasive species themselves, their impacts on ecosystems are another important factor in designing and implementing an incentive management plan. Removal of one invasive species provide resources for other species to survive. For example, removal of wild pigs (*Sus scrofa Linnaeus, 1758*) and sheep (*Ovis aries Linnaeus, 1758*) in Hawaii increased the opportunity for flammable invasive grasses to grow in the state's lowlands, which increases frequency of fires (Pasko et al., 2014). Invasive-species managers need to carefully evaluate interactions among native, and non-native species in their environment before implementing any inventive program.

Human Health Factors

Another necessary step in designing an incentive program is to evaluate a targeted species' impacts on human health, either when consuming them for food or handling them during capture. During lionfish tournaments in Florida, participating divers are required to use spears and nets for catching. However, the lionfish's venomous spines can cause pain and swelling and even tachycardia, seizures and temporary paralysis of humans when handled them improperly (Morris et al., 2009). For those invasive species that are harvested for food, a full health assessment is necessary (Pasko et al., 2014).

Socioeconomic Factors

Socioeconomic considerations such as costs, profits and risks are important factors for any incentive program. Invasive species always lead to losses in the ecosystem and the economy and species managers need to evaluate the financial costs and risks of either eradication programs or long-term sustained control operations (Pasko et al., 2014).

Long-term ecosystem and economic losses help to determine the overall goal of a program. Bomford and O'Brien (1995) found that the nutria eradication program in Great Britain was successful because the value of agricultural and environmental resources protected was greater than the costs of program: Each captured animal was worth more than $600, totaling more than $3 million.

In the process of creating an incentive program, determining factors include harvested commodities' value, harvest costs, harvesters' minimum acceptable profit, and the value of protected resources. A bioeconomic model integrates those factors can help determine the effectiveness of incentives in controlling targeted species population. A bioeconomic analysis of Louisiana's Coastwide Nutria Control Program (CNCP) concluded that increasing incentives help harvest more numbers of nutria, and that CNCP is an effective method of controlling Louisiana's nutria population (Dedah et al, 2010). However, an incentive program may have unintended outcomes. One is that some people will even raise non-native species and release them to profit from bounty programs or commercial market (Pasko et al., 2014).

Government Intervention

Government intervention can play an important role in any incentive programs. For a targeted invasive species with little commercial value, such as small size Asian Carp, governments may provide seed funds to encourage consumers and private industry to participate in eradication programs. Governments formulate the appropriate administrative and legislative rules that guarantee that incentive programs will proceed effectively. In 2013, Florida's Fish and Wildlife Commission waived catching licenses, determined the types of acceptable catching gear types and eliminated catch limits on lionfish to make accessing them more convenient (Pasko et al., 2014).

Outreach

Incentive programs also contribute to raising public awareness of targeted invasive species' threats and actions. In Florida, Reef Environmental Education Foundation (REEF) provides educational seminars before each annual lionfish derby and prepares lionfish dishes for participants and tourists to sample (Morris, 2012; Pasko et al., 2014).

2.1.3 Incentive Management Methods

There are four major incentive programs defined in Pasko and Goldberg (2014) in their article that encourage harvest of invasive species.

Bounty Program

Bounty Program. An alternative to the popular derby is the bounty program, in which a predetermined amount of money is paid to an individual upon satisfactory evidence of collection of a specified organism (Pasko et al., 2014).

In January 2002, Louisiana established the Coastwide Nutria Control Program (CNCP) for registered participants with an economic incentive payment of $4 per nutria tail. Cheikhna Dedah and Richard Kazmierczak developed a bioeconomic supply model that helps explain nutria harvests' relations with a suite of economic and environmental factors (Dedah et al., 2010). This article suggested that nutria harvest is both related to the price paid for each animal and environmental factors. It also suggests that the price should be increased to $5 instead of $4 to achieve the goal of harvesting 400,000 nutrias per year.

CNCP's 2015-2016 report shows obvious effects of CNCP in the years from 2002 to 2016. As shown in Figure 2.1, the nutria harvest has stabilized after several years of CNCP, and there is an obvious effect that damaged herbivory has decreased as observed in a series of surveys.

Table 2.1 presents the number of nutria harvested per year and herbivory damage. The average nutria harvest in coastal Louisiana has reached $337,947 + / - 60,119$ standard deviation per year. Total harvest of nutria over the past 14

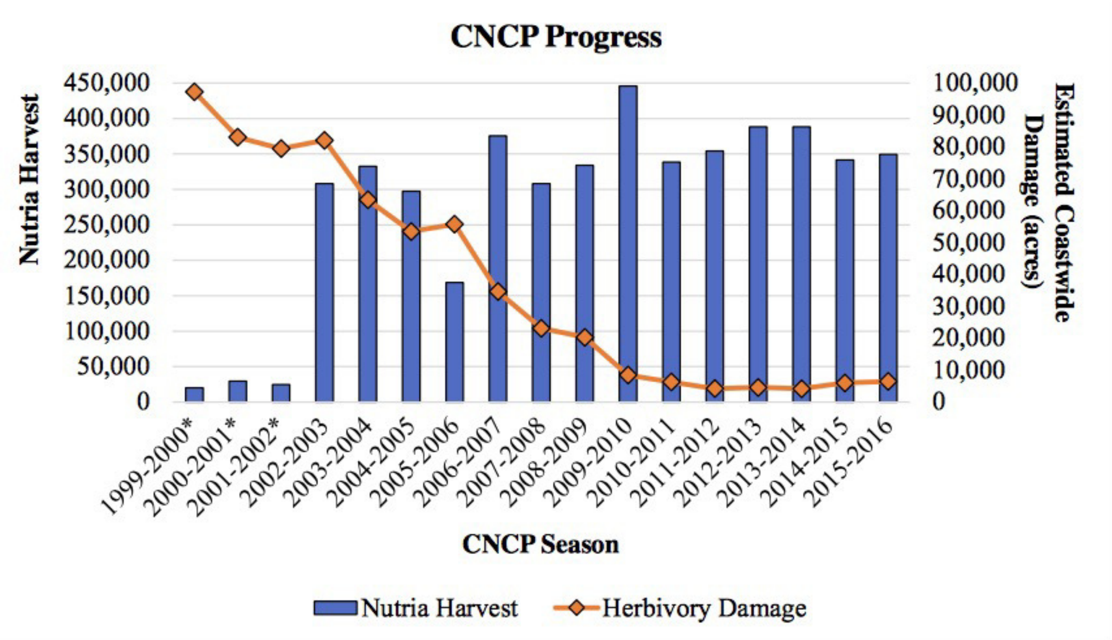


Figure 2.1: Nutria Harvest and Coastwide Nutria Herbivory Damage (Source: Coastwide Nutria Control Program 2002 to 2016)

	Nutria Harvested		Herbivory Damage (acres)
1999-2000	20,110	2000	97,271
2000-2001	29,544	2001	83,021
2001-2002	24,683	2002	79,444
2002-2003	308,160	2003	82,080
2003-2004	332,396	2004	63,398
2004-2005	297,535	2005	53,475
2005-2006	168,843	2006	55,755
2006-2007	375,683	2007	34,665
2007-2008	308,212	2008	23,141
2008-2009	334,038	2009	20,333
2009-2010	445,963	2010	8,475
2010-2011	338,512	2011	6,296
2011-2012	354,354	2012	4,233
2012-2013	388,160	2013	4,624
2013-2014	388,264	2014	4,181
2014-2015	341,708	2015	6,008
2015-2016	349,235	2016	6,496

Table 2.1: Nutria Harvest and Herbivory Damage from 1999 to 2016 (Source: Coastwide Nutria Control Program 2002 to 2016)

seasons has reached 4,731,263 (CNCP, 2015–2016)

Contract Operation

Contract Operation. Similar to a bounty but based on a fixed number, a contract operation provides direct payment to the public or service provider to remove or harvest a species (Pasko et al., 2014).

One example of using a contract operation to control an invasive species is the capture of Rhesus Monkeys in Florida. Trappers with state permission can catch targeted animals and sell them to specified institutions or to the government. Over the past decade, a trapper named Scott Cheslak, has captured approximately 700 of the juveniles or yearlings monkeys from the wild. He continues to trap those monkeys and sells some of them to a research facility according to USDA rules (Gillespie, 2013).

However, there have been voices within animal protection foundations that have argued that the Rhesus Monkey should be protected for its natural beauty. The animals are also prized for their contribution to a positive test for herpes B virus, a virus that can be fatal to humans (Pittman, 2013).

Commercial Market

Commercial Market. This is an effort that is undertaken, usually privately, when a perceived market exists for a species that can be harvested and offered for sale (Pasko et al., 2014).

Commercial marketing has become one of the most important strategies to reduce the population of invasive carp, particularly black carp (*Mylopharyngodon piceus*) and bighead carp (*Hypophthalmichthys nobilis*), and also silver carp (*H. molitrix*) in the Mississippi River Basin (Asian Carp Regional Coordinating Committee (ACRCC), 2012). It includes attempts to develop Asian Carp products. For example, the Baton Rouge, Louisiana-based Silverfin Marketing Group, created by Chef Philippe Parola, tried to create Asian Carp food for the domestic and international markets. In Asian markets including China and Korea, there is great demand for cheap Asian Carp. Two Rivers Fisheries, based in Wickliffe, Kentucky, shipped out 264,000 tons of Asian Carp (beheaded, dressed and frozen) in 2014. Two Rivers bought between 6,000 and 8,000 tons of Asian Carp daily from fishermen in Kentucky and Missouri. In 2015, the state of Kentucky subsidized the rate paid to commercial fishermen at a price of at least 15 cents per pound for the fish. Before 2015, some processors have paid between 8 and 10 cents per pound (Downs, 2016).

Recreational Harvest

Recreational harvest actions enhance or encourage recreational fishing, hunting, or trapping of invasive species by conducting outreach, modifying seasons, or changing license requirements or bag limits (Pasko et al., 2014). The tournament is one of the major management tools of recreational harvest. Examples of invasive-species tournaments are listed in next section.

2.2 Tournament as a Management Tool

2.2.1 Python

In 2013 the Florida Fish and Wildlife Conservation Commission held a month-long Burmese Python (*Python molurus bivittatus*) catching tournament with cash prizes. Because the tall grasses of the Florida Everglades make it difficult to spot and catch pythons, only 68 snakes were caught out of an estimated population of approximately 30,000 to 100,000 total population (Hoag, 2014)

The difficulty of capturing the cryptic Burmese Python in the Florida Everglades means that much more monitoring efforts are needed, and perhaps increased incentives, while also attending to the safety of snake hunters working in that wild environment (Pasko et al., 2014).

2.2.2 Asian carp

In August 2016, I visited Bath, Illinois, and joined in the Redneck Fishing tournament, a two-day event held every year. On each of the two days there are two heats, one starting at 12 pm and the other at 4 pm. The entry fee is $60 per boat per heat (unless prepaid before the event for $50). Participants are allowed to use only dip nets to catch Asian carp as the fish jump out of the river.

Four cash prizes are awarded each day (regardless of the heat) for the greatest number of fish caught. According to Betty Deford, organizer of the Redneck Fishing Tournament, the size of the prize depends on how many boats register that day. At the end of the day all of the caught fish are donated to a local fertilizer factory.

The competition takes place on a seven-mile stretch of the Illinois River with Bath at the center. Even though there is an inland lake behind this stretch of river, competition is allowed only in this shallow and narrow seven-mile stretch. More Asian carp jump out of the water here due to the shallowness.

2016 was the 11th annual Asian carp tournament in Bath. Most of the participants came from nearby cities and had participated at least once before; but there were also participants from as far away as New York. (YouTube videos of the unlikely sight of flying fish being caught in mid-air helped to popularize it.) On the first day, approximately 2,800 fish were caught by fishermen registered in 21 boats and $300 was awarded to the first prize boat. The record number of fish caught in the two-day tournament was 10,631 in 2013. According to Deford, it cost between $6,000 and $7,000 to stage the event. In addition to fishing, participants could eat and listen to live band music. A kind of Asian carp soup was provided to introduce participants to Asian carp dishes.

In 2016 there were a total of 3,690 carp caught by 77 registered boats. Although this was the 11th time the Redneck Asian carp fishing tournament had been held, many organizers and members of the public did not realize that this was more than a recreational weekend stunt: that it was also an effective way to control an invasive species. There was a noticeable lack of information about this at the tournament.

(a) (b)

Figure 2.2: Redneck Asian Carp Tournament in Bath, Illinois

2.2.3 Lionfish

The Reef Environment Education Foundation (REEF) has organized a lionfish derby each year since 2010. Participants are allowed to use only spears and nets to catch lionfish on coral reefs in competition areas. Derby organizers measure each fish's length and award prizes for the most fish caught, biggest fish caught, and smallest fish.

Before and after the derbies in Key Largo and the Bahamas in 2012 and 2013, Dr. Stephanie Green counted lionfish at 60 sites: Lionfish density declined more than 60% over a 100–150 km^2 area after competition. Although lionfish recolonized the sites within six months, their size was much smaller and this reduced the pressure on the reefs (Hoag, 2014).

2.3 Bioeconomic Model

There are three main studies of lionfish derbies in Florida that analyze the impacts and effectiveness of the events in controlling invasive species. The first research, by Dr. Green, constructs an ecological model based on the assumption that the lionfish preys on native species. Lionfish threshold density occurs when the net rate of native prey biomass is zero, meaning that lionfish consume all the available prey. This model is only ecological, it has no socioeconomic factors. Green found that reductions in lionfish density of 25% to 92% were required, depending on the fishing site. (Hoag, 2014).

The second research, also by Dr. Green, is a study of lionfish derbies: Volunteers culled lionfish during annual derby events from 2012 to 2014 in Bahamas and Florida and it was found that they reduced lionfish densities by 52% over 192 km^2 on average each year. In her analyses of derbies, Dr. Green and her research team calculated the total area fished during each derby (total habitat over which the teams fished during each tournament), and REEF recorded the number and size of fish collected lionfish. She found that derby participants helped to reduce an average of 57% lionfish densities within the derby-designated areas. Lionfish size increased over time on Florida habitats that total invader biomass rebounded to pre-culled levels after each derby. Dr. Green summarizes three potential reasons for lionfish recolonization rates: (1) Lionfish population in Key Largo, Florida is in a stage in their trajectory of population quick increase. (2) High-complexity coral patch reefs and artificial structures provide lionfish food and rest resources. (3) Movement of adult lionfish from adjacent habitats has important impacts in colonization (Green et al., Unpublished).

The third research, conducted by Cruz, Chaves, and Cote (2014), suggests that management of invasive species can be facilitated by public participation. Information was collected on 69 lionfish derbies held in the wider Caribbean region from 2010 to 2015. These researchers found that derbies attended mainly by artisanal fishers reported lower catches but more participation than derbies attended by recreational divers or a mixed public. Participation was best predicted by national wealth (GDP per capita) and the number of local dive shops.

All of the research to date has tried to evaluate various aspects of the problem, mainly from either an ecological or a socioeconomic point of view. There is no research that combines these two factors to generate a bioeconomic model that will simultaneously predict human behavior and lionfish population thresholds. The model presented here merges ecological and economic factors.

A dynamic optimization model can help to solve this problem. In a book on resource economics (Conrad, 2010) it is stated that there are two key features of the dynamic optimization problem: 1) state equation in a dynamic optimization system helps to restate natural resource evolution over time; and 2) decision in time period t will affect the level of state variable in the next period t + 1. With an objective function that usually maximizes or minimizes some net economic values and subjects to relevant constraints, solution to a natural resource optimization problem will be a 'time path,' indicating optimal resource extraction in each period, or a 'policy' indicating how resource stock can affect harvest.

CHAPTER 3

BIOECONOMIC MODEL

We consider the making of a dynamic optimization model in two parts: objective function and constrained conditions. Our objective function is to minimize the discounted value of the sum of each period's environmental costs and derby prize money. The constrained conditions of the annual derby illustrate that lionfish populations grow again between successive years and the decision of whether a derby should be held is decided by the amount of prize money that can be raised and by lionfish density. The model is a standard bioeconomic dynamic optimization model as described by Colin W. Clark (2010).

3.1 Logistic Net Growth Function

To describe a lionfish derby in mathematical terms, it is first necessary to make clear the lionfish net growth pattern.

A basic renewable-resource exploitation model describes the lionfish growth pattern. This model is sometimes used in fisheries (Clark, 2010):

$$\frac{dx}{dt} = G(x) - h(t), \quad t \geqslant 0 \tag{3.1}$$

$$x(0) = x_0 \tag{3.2}$$

where $x = x(t)$ denotes lionfish biomass at time t (x_0 means initial lionfish stock at time $t = 0$).

The general production model $G(x)$ in equation (3.1) represents the net natural-growth rate of the lionfish population biomass that depends on its current biomass. Here lies an assumption that the production model $G(x)$ does not involve lionfish population structure, such as the age of individuals or spatial distribution (Clark, 2010). The natural growth function $G(x)$, e.g. General Production Function, satisfies the following three assumptions:

$$G(x) > 0 \; for \; 0 < x < K \tag{3.3}$$

$$G(0) = G(K) = 0 \tag{3.4}$$

$$G''(x) < 0 \; for \; 0 < x < K \tag{3.5}$$

where K is the environmental carrying capacity for the given population.

Equation (3.3) tells us that the production function $G(x)$ which depends on current lionfish biomass is always greater than zero if the lionfish biomass is between none and carrying capacity. Equation (3.4) tells us that lionfish production is none when there are no lionfish (e.g. $x = 0$) or lionfish biomass reaches the upper limit of environmental constraints (e.g. $x = K$). $x = 0$ is an unstable equilibrium since $\frac{dx}{dt} > 0$ for small $x > 0$ (when $h = 0$). It means that population will necessarily recover over time if harvesting ceases. Eradicating the last number of population is really hard to achieve in reality. $x = K$ is a stable equilibrium for a population not beging harvested. The reason is that the case $x > K$ never happens under natural conditions (Clark, 2010). Equation (3.5) tells us that the rate of marginal production is negative, which means that marginal production decreases when stock size increases. In Figure 3.1, the upper figure presents the general production function where the bottom figure presents the marginal production function. In addition, several obvious assumptions needs to be made

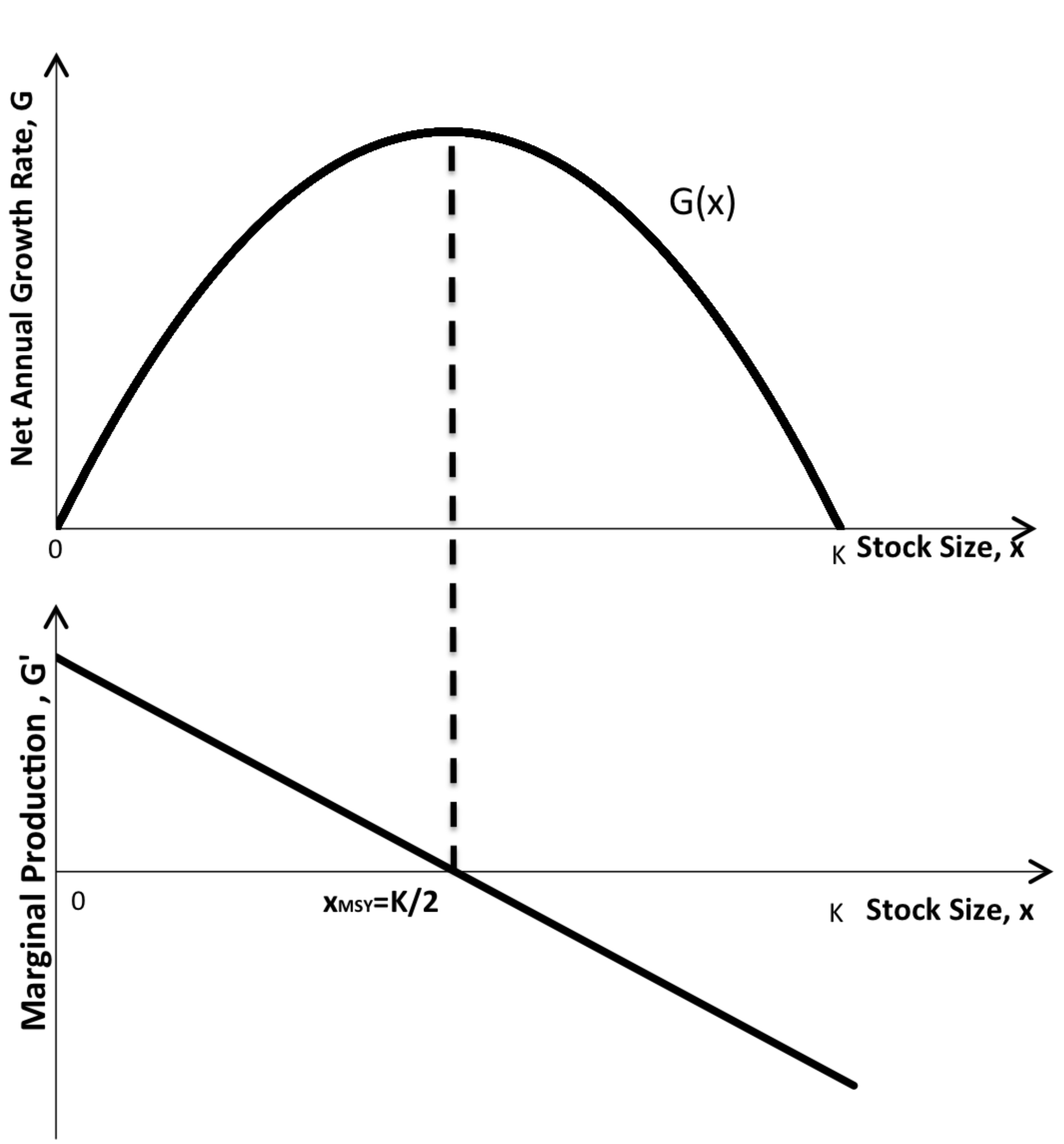


Figure 3.1: Production Function and Marginal Production Function

clear: (1) the lionfish derby in Key Largo involves a single species in an unstructured population; (2) it has constant parameters; (3) it is deterministic; and (4)it has no seasonal variation (Clark, 2010)

Ecologists refer to $\frac{dx}{dt} = G(x)$, $x(0) = x_0$ as a harvest-free resource model under

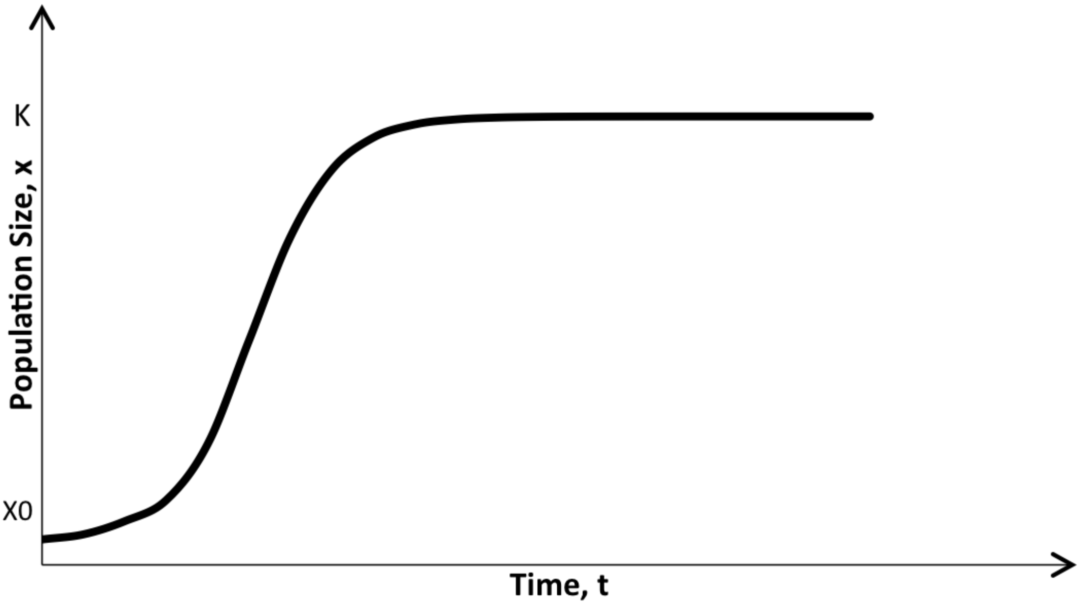


Figure 3.2: Logistic Net Growth Function with Time

density dependence (May, 1981; Walters et al., 2004).

With assumptions (3.3) to (3.5), the following functional form for $G(x)$ is called the logistic net growth model:

$$G(x) = rx(1 - \frac{x}{K}) \tag{3.6}$$

where r is the intrinsic growth rate of the population. When $x = x_0 << K$, the population is growing in an approximately exponential way; it eventually approaches but never reaches or crosses the carrying capacity over time. Figure 3.2 shows the population growth pattern of production function (Clark, 2010).

We then turn back to Figure 3.1, where the marginal production function is positive when the stock size is small, but continues decreasing over different stock sizes and becomes lower than zero gradually. What happens to the general production function is that the biomass is increasing at a decreasing rate when marginal production is greater than zero. Then the general production function reaches its highest level at the stock size where marginal production is zero. Finally, the general production function begins to decrease in an increasing rate after marginal production across the stock size is zero and continues decreasing.

The local maximum stock size where marginal production reaches zero is also called *Maximum Sustained Yield*, which means the largest harvest rate that can be sustained indefinitely (Clark, 2010). By using equation (3.6), we get:

$$
\begin{aligned}
G(x_{MSY}) &= r x_{MSY}(1 - \frac{x_{MSY}}{K}) \\
G'(x_{MSY}) &= r(1 - \frac{2x_{MSY}}{K}) = 0 \\
x_{MSY} &= \frac{K}{2}
\end{aligned}
$$

3.2 Harvest Function

In equation (3.1) $h(t)$ represents the rate of removal, or harvest, of lionfish biomass at time t (Clark, 2010). We can incorporate human behavior, such as lionfish derby participation, and predict the outcome under various conditions.

Here we adopt the Scheafer catch-effort harvest function:

$$h = qEx \tag{3.7}$$

$E(t)$ is a function of time t and represents the harvesting effort at time t. Harvesting effort means the number of (standard) vessels actively fishing at time t.

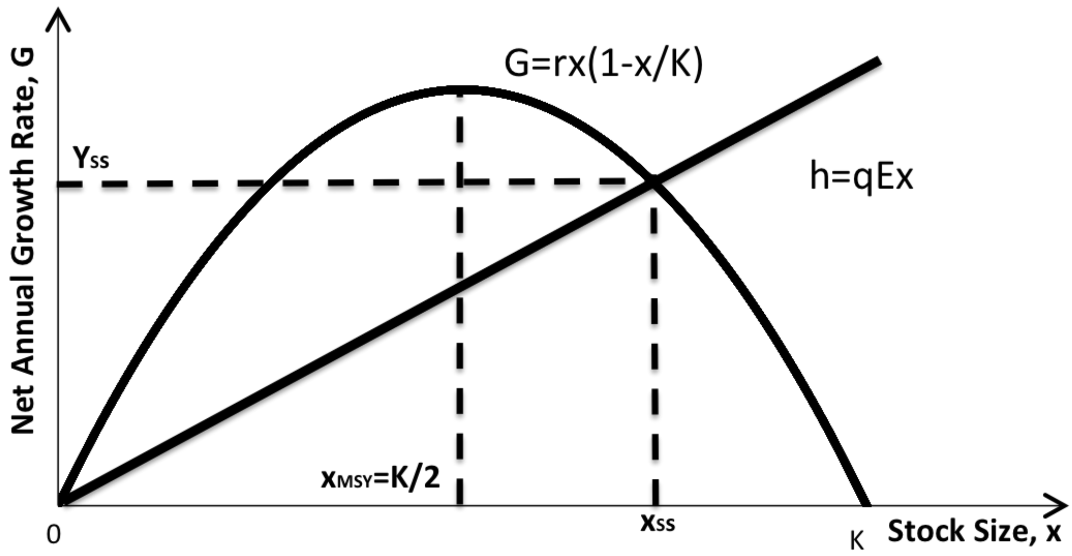


Figure 3.3: Feedback Harvest Policy

The units would then be Standard Vessel Units (SVU). $q > 0$ is a constant called the catchability coefficient: it represents how much of the current biomass x_t can be exploited by one standard vessel in one time unit (Clark, 2010). The Scheafer catch effort harvest function is a special case of the Cobb Douglas production function $H_t = qx_t^{\alpha}E_t^{\beta}$ where $\alpha = \beta = 1$. It is called the catch-per-unit-effort (CPUE) production function (Conrad, 2010).

Equation (3.10) is also called *feedback harvest policies* that express harvest as a function of stock size. Since q is a constant and E is fishing effort with no relation to stock size x, the feedback harvest policies function is a line through the origin. The intersection of $G(x)$ and $h(t)$ is called steady-state equilibrium such that the production of fish stock equals harvest rate. We can observe it from equation (3.1).

$$\frac{dx}{dt} = x_{t+1} - x_t = G(x) - h(t), \quad t \geqslant 0$$

When

$$G(x) - h(t) = 0, \quad G(x) = h(t) = Y_{ss}$$
$$\frac{dx}{dt} = x_{t+1} - x_t = 0, \quad x_{t+1} = x_t = X_{ss}$$

In the steady state, each period's fish stock and harvest rate always keep to the constant levels of X_{ss} and Y_{ss}, and they are sustainable *ad infinitum* (Conrad, 2010).

3.2.1 Functional Form of Fishing Effort E_t

The next problem is how to measure the fishing effort of a lionfish derby in Key Largo, Florida. In the next chapter I will describe in detail how the lionfish derby proceeds. A few key features of the derby describe the fishing effort's functional form:

(1) All participants are divided into teams and each team has a maximum of four people.

(2) The lionfish derby in Key Largo is held on a single day each year, typically from sunrise to sundown in the summer.

(3) Participants are allowed to use only spears and hand-held nets, not fish-

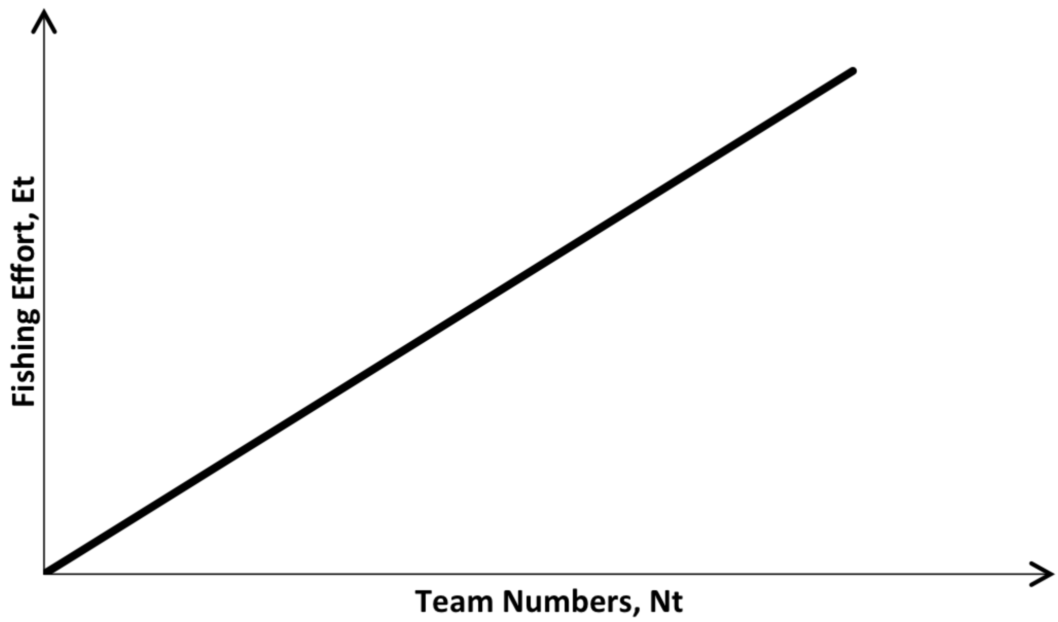


Figure 3.4: Fishing Effort Team Number Relation

ing poles or mechanized nets; they typically dive down to the coral reef to catch lionfish in the competition area; and teams are required to return to the recording station at the end of the day to calculate their lionfish biomass.

(4) The competition area is a 50-mile range near where the recording center is set up on shore: a known lionfish habitat.

These four facts help simplify the fishing effort function. Participants' fishing efforts do not need to be measured individually; they can be measured by teams instead. Because all of the teams have identical fishing time, fishing environment, and fishing equipment, each team's fishing effort is the same in one standard vessel unit. Total fishing effort can then be measured by the number of teams that actively fished during the hours of the derby.

We define N_t as the number of four-person teams, then

$$E_t = aN_t \tag{3.8}$$

is a level of effort in a derby, where a is assumed to be greater than 0; as more teams participate in this derby, there will be more total fishing effort.

3.2.2 Team Numbers N_t Explained by Derby Prizes

The number of participating teams is regarded as a function of prize money offered

$$N_t = p_t^{\beta} \tag{3.9}$$

where β is the congestion parameter, and $0 < \beta < 1$. Figure 3.5 helps explain where congestion comes from: the large rectangle represents the 50-mile area near shore where the lionfish derby is held; the triangles represents the coral reef where lionfish rest; and the stars represents teams of fishermen. The teams anchor their boats near the reefs and members dive into the water to catch lionfish. Coral is not distributed uniformly in the derby-designated area, and several teams may surround the same cluster of coral.

Three assumptions are needed for the four-person teams-prize relation function.

(1) As prize money goes up, more participants are attracted to the derby and the number of participating teams goes up.

(2) $0 < \beta < 1$.The number of teams increases at a decreasing rate with in-

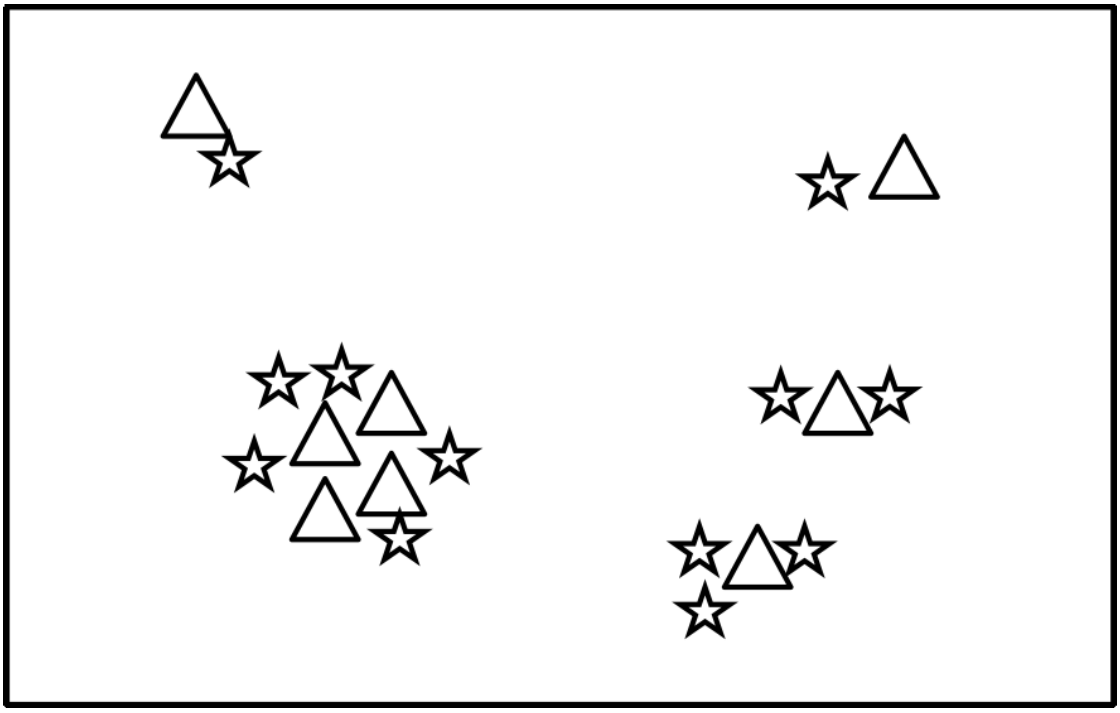


Figure 3.5: Lionfish Derby Area Example

Figure 3.6: Four-Person Team Number and Prize Relation

creasing prize money. Let's make an extreme guess: when award prize is extremely large, an increase of one dollar or any small unit of change in prize money will not attract another unit of participating teams. Participants will think the change is too small to generate more interest in the derby. Thus, the number of four-person teams increases as a strictly concave function of prize money which is shown in Figure 3.6.

(3) Although ecologists may argue that there will be fun-seeking participants even without the offer of prize money, economists are interested in the impact of prize money; so functional form is simplified around the concept of team numbers, not individuals.

3.2.3 Transformed Harvest Function

Now, the harvest function can then be transformed to this:

$$H_t = qE_t x_t = qaN_t x_t = qa(p_t^{\beta})x_t = mp_t^{\beta}x_t \tag{3.10}$$

where $m = qa > 0$ is the coefficient of harvest function; $0 < \beta < 1$ is congestion parameter; p_t is award prize at time t; and x_t is lionfish biomass at time t.

3.3 Incentive Sector: P_t

The incentive of a tournament, such as a derby, is different from a bounty program. A bounty awards participants money for each unit of a species hunted while a tournament is a contest that awards prize money to only the most successful hunters. From the point of view of an invasive-species manager, it may be advantageous to pay derby winners an amount of money to help reduce invasive species biomass—without having to pay the less successful hunters, too.

In the lionfish derby in Key Largo, prize money is awarded to three groups:

(1) The team that collects most number of lionfish.

(2) The team that finds the biggest lionfish.

(3) The team that finds the smallest lionfish.

It may be argued that prize money should be awarded to the team that lands the greatest number of lionfish, and prizes for biggest and smallest fish make no economic sense in using a derby to reduce invasive species biomass. However, if a team catches a great number of lionfish, there is a higher probability of catching a variety of lionfish of bigger and smaller sizes. Thus, prizes for lionfish sizes can trigger participants' interests in catching more fish. For example, 2016 Key Largo lionfish derby information collected from REEF shows that the winning team, called Rob's Angels, caught the most number of lionfish, a total of 113. This team was also awarded the biggest prize for the largest lionfish: they caught a 41.4 cm lionfish among their 113 fish. This same team, Rob's Angels, was awarded the prize for the smallest lionfish, a 9 cm specimen. Thus, catching more lionfish will increase the probability of catching the biggest and smallest lionfish of the day. So awarding prizes for the biggest and smallest lionfish will drive participants to catch more fish. For my estimation and analysis, I summarize the three prizes and treat them as one big prize at each time t.

3.4 Environmental Damage is a Function of Invasive Species Density

The environmental damage caused by lionfish can be evaluated using a travel cost model or contingent valuation method. However, there is not enough information to construct these two models. We have little direct information, and even less data, on lionfish damage. An alternative method to determine an upper bounds for lionfish environmental damages is to list all invasive species in a targeted study area. The Appendix lists all invasive species in Key Largo. Information on these invasive species is not sufficient for an estimation. Conrad (2010) makes two assumptions for lionfish environmental damage function:

Assuming that $k(x_t)$ is damage in year t when lionfish biomass in year t, then

(1) Larger pollution stocks (lionfish) will result in higher damage $k^{'}(x_t) > 0$.

(2) Damage might be 'smoothly' increasing at an increasing rate $k^{''}(x_t) > 0$

Assumptions (1) and (2), imply that the damage function is strictly convex to lionfish biomass. Thus, the lionfish environmental damage function can be written as equation (3.11) that is strictly convex.

$$k_t = \frac{d}{2}x_t^2, \quad d > 0 \tag{3.11}$$

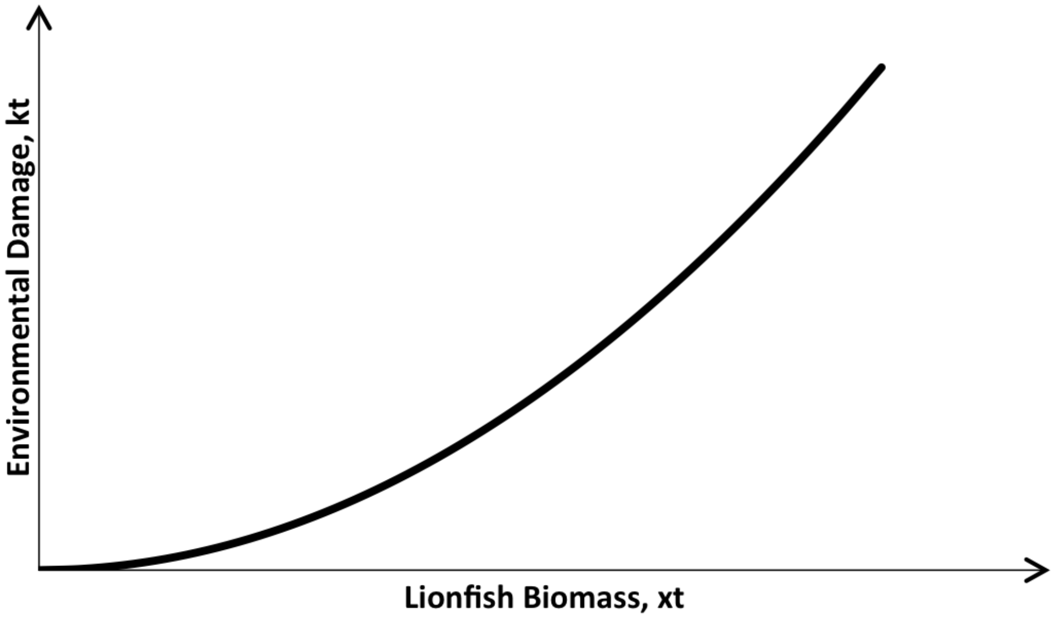


Figure 3.7: Lionfish Environmental Damages

3.5 Dynamic Optimization Model Equation

I can then construct the dynamic optimization model. The objective function means that the invasive-species managers' goal is to minimize the sum of each period's value of environmental costs plus derby prize money. $C_t = k_t + p_t$ is total costs of lionfish at time t.

$$\underset{[x^*,p^*]}{\text{Min}}\ C = \sum_{t=0}^{T} \rho^t [k(x_t) + p_t] \tag{3.12}$$

subject to

$$x_{t+1} - x_t = G(x_t) - h(p_t, x_t),\ given\, x_0 > 0 \tag{3.13}$$

$$If\ x_t \geqslant x^*,\ p_t = p^* \tag{3.14}$$

$$If\ x_t < x^*,\ p_t = 0 \tag{3.15}$$

It is important to clarify what our model will solve in the end. Two unknowns, x^* and p^*, that are the key variables for growth patterns and harvesting strategies. Invasive-species managers are goal oriented. They establish harvest levels by setting prize monies and appropriate biomass density to trigger a derby. To be more specific, invasive-species managers designate a certain level of biomass density x^* before holding a tournament. When biomass exceeds this level, the manager will hold a tournament and set prizes p^* accordingly. If the invasive species has not recovered, then a tournament is not held and nobody receives an award. The threshold $[x^*, p^*]$ and other factors work together to reach equilibrium. By choosing appropriate x^* and p^*, invasive-species managers wish to reach the goal of minimizing present total costs, subject to three constraints. First, the change of invasive-species biomass between year $t+1$ and year t is the invasive species' natural growth minus harvest in year t, given that the initial invasive-species biomass in the competition area is also greater than 0. Second, if invasive species density in year t is the same or greater than threshold x^*, then this means that the invasive-species manager should hold a fishing tournament and set the prize money p^* at the appropriate level to help control fish density in the competition area. Third, if invasive species density in year t is less than threshold x^*, then density has not reached the level to hold a fishing tournament. Organizers should not hold a fishing event at this time, thus the award prize is 0.

We assume that natural growth function is:

$$G(x_t) = r(1 - \frac{x_t}{K})x_t \tag{3.16}$$

where r is the intrinsic growth rate and K is the environmental carrying capacity.

The environmental cost function is in a quadratic format:

$$k(x_t) = \frac{d}{2} x_t^2 \tag{3.17}$$

where $d > 0$ is the estimation of damage coefficient.

The harvest function:

$$h(p_t, x_t) = m p_t^{\beta} x_t \tag{3.18}$$

$m > 0$ is the coefficient of harvest function. $0 < \beta < 1$ is congestion parameter; p_t is award prize in year t; and x_t is lionfish biomass at time t.

CHAPTER 4

LIONFISH

Like many other invasive species, lionfish invade a new area along a theoretical trajectory that has four patterns: lag phase, exponential growth, invasion peak, and equilibrium (Figure 4.1). As Morris (2012) points out in report, invasive species population peak can exceed the carrying capacity of the new system. After a lionfish population crosses the invasion peak (which is always beyond the carrying capacity), other factors drive a lionfish population to equilibrium, including competition with native species or for food and space, predation (including cannibalism), parasitism and disease, and abiotic factors such as water temperature (Morris, 2012).

The lionfish is one of the most serious threats to coral reefs. Not only does the fish destroy the reef's food web, it can also have an impact on commercial fisheries, tourism, and overall health of a reef, which leads to great economic losses (Morris, 2012).

4.1 Biologcal and Ecological Features of Lionfish

4.1.1 Biological Characteristics

Genetic analysis suggests that nearly a dozen lionfish were originally released in the waters off the Florida coast. These were mainly two species of lionfish: devil firefish (*Pterois miles*) and red lionfish (*P. volitans*) (Hammer et al., 2007; Freshwater et al., 2009; Hoag, 2014).

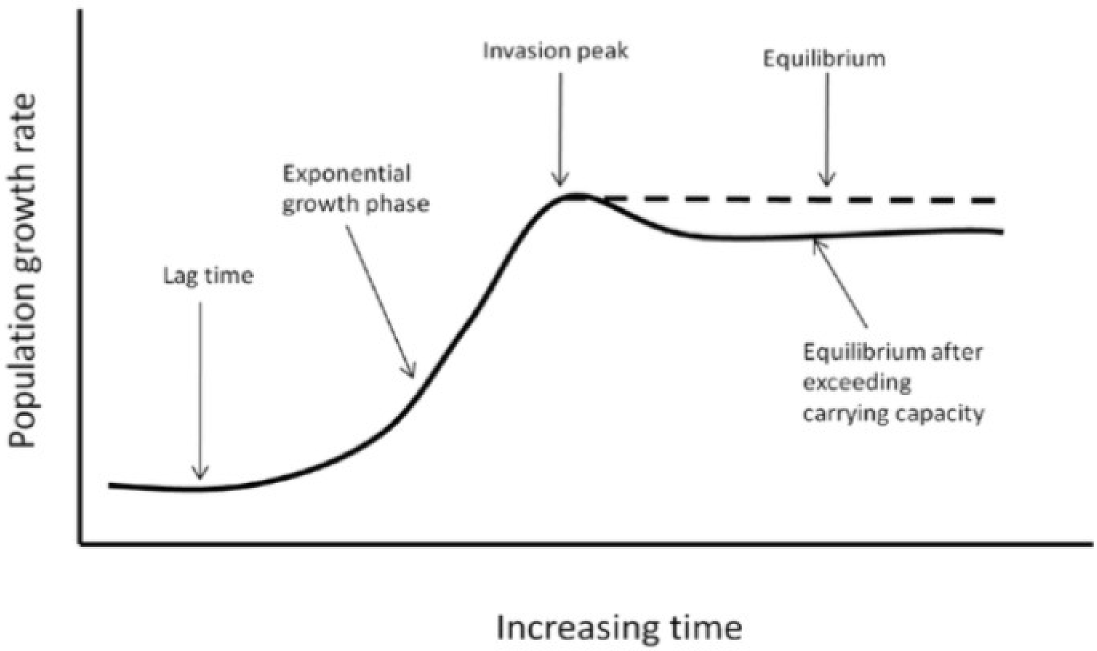


Figure 4.1: Lionfsih Predictable Trajectory (Source: Morris, 2012)

Lionfish are general carnivores preying on a wide variety of fish and crustaceans (Morris et al., 2009; Cote et al., 2013). DNA analysis of 157 lionfish stomachs from fish that were caught in the Mexican Caribbean found that these lionfish had consumed 43 crustacean and 34 fish species, including parrotfish, French grunt and graysby that are an important food for local people (Hoag, 2014).

The spines of the lionfish, except for the caudal spines, contain apocrine-type venom glands. As Halstead (1955) indicate, each spine is encased in an integumentary sheath or skin and contains two grooves of glandular epithelium that comprises the venom producing tissue. Lionfish envenomation happens when a spine enters the victim and its integumentary sheath is depressed (Morris, 2012). Because of this powerful weapon, lionfish have been documented to consume prey more than 40% of their total length—which means that lionfish that are more than 40 cm long can consume fishes and crustaceans up to 15 cm (Morris, 2012).

4.1.2 Geographic Range

Lionfish (*Pterois volitans*) first showed up on the eastern seaboard of the United States in the 1980s, preying on coral reef fish. A lionfish was first sighted near Fort Lauderdale, Florida, in 1985. The fish quickly spread more than 4 million square kilometers throughout the Caribbean Sea, Gulf of Mexico and Atlantic coastline. They are now found from North Carolina to Venezuela (Hoag, 2014), but Figure 4.2 shows the status lionfish in 2015 that they are as far as north as New York State. The lionfish invasion has occurred rapidly in a wide geographic range, so it seems likely that the invasion will continue to expand.

The lionfish habitat is unusually broad: The fish can live anywhere from the surface of the sea to more than 300 meters deep. Usually they are found near coral and hard bottoms, artificial reefs, mangroves, canals, seagrass beds, ledges, sand holes, and rocky shorelines. They usually rest under ledges or in sheltered bottom areas during midday hours; they are active in the low light of dusk and dawn (Morris, 2012).

4.1.3 Reproduction

Male and female lionfish exhibit minor sexual dimorphism during spawning time. The two genders are hard to distinguish visually (Fishelson, 1975). Gener-

Figure 4.2: USGS: Lionfish Status in 2015

ally, males grow larger than females. The largest recorded male lionfish was 476 mm (Morris, Unpublished Data). (Note that 1 cm = 0.394 inches, lionfish that is 47.6 cm is 18.75 inches long). Fishelson (1975) reported that in courtship, male and female lionfish circle each other, side-wind, follow, and lead one another. This ritual begins before dark and continues into nighttime hours.

Lionfish can spawn two million eggs a year. They have few predators or competitors in the areas to which they are introduced. Based on collections from North Carolina and the Bahamas, it is suggested that lionfish reproduce in all seasons of the year, nearly every 34 days (Morris, 2009). The settlement age of lionfish in the Atlantic is estimated to be approximately 20-35 days within a mean of 26.2 days (Ahrenholz et al., 2012).

4.1.4 Ecological Effects

Lionfish prey on some herbivorous species that have great effort in cleaning algae off coral reefs and compete food and space resource with economically important species like snapper and grouper (Morris, 2012). Simulations by Jesus Ernesto Arias-Gonzalez at the Center for Research and Advanced Studies of the National Polytechnic Institute, in Merida, Mexico, have predicted that 10% of coral biomass would be decreased from lionfish invasion within ten years (Hoag, 2014).

An experiment by Alins and Hixon (2008) reported a 79% reduction in fish recruitment on experimental patch reefs in the Bahamas for a five-week observation period. An average of a 65% decline in prey biomass have occurred in the Bahamas over a two-year period (Green et al., 2012a). Lionfish consume a series of species and sizes of native fish and invertebrates, including cryptic and small-bodied species and the juvenile size classes of larger bodied species (Green et al., 2012a). Research shows that lionfish grow much faster and consume prey at much higher rates than native Coney grouper (*Cephalopholis fulva*), leading scientists to be concerned that lionfish may outcompete these native fish in invaded reefs (Albins, 2012).

Figure 4.3: Potential Lionfish Prey: Masked Goby (top-left), Secratery Blenny (top-right), Nassau Grouper (bottom-left), Spanish Hogfish (Source: Morris, 2012)

Besides the direct effect of causing native species to vanish, the lionfish will also cause indirect effects on the entire marine food web if their invasion influences the benthic communities. One of indirect effects of lionfish can be its predation depletes grazers' population that control coral-algal dynamics (Morris, 2012).

4.1.5 Socioeconomics Effects

The socioeconomic impacts of the lionfish invasion haven't been quantified yet, but they can be observed in the fishing and tourism economies (Morris, 2012). As indicated in Morris's and Akins's 2009 report, lionfish predation on econom-

Figure 4.4: Potential Lionfish Competitors: Nassau Grouper (top-left), Black Grouper (top-right), Coney Grouper (bottom-left), Caribbean Spiny lobster (Source: Morris, 2012)

ically important species, such as juvenile serranids, could result in a decrease in landings, hamper stock rebuilding efforts, and slow conservation-based initiatives (Morris et al., 2009). Since lionfish have venomous spines that will release a toxin when they encounter divers, there is a risk of human harm and a potential reduction in recreational activities. Fishermen, divers, beachgoers, and those in the restaurant trade where lionfish are a food fish have higher than average possibilities of encountering them.

For fishing economies, lionfish may affect the catch per unit effort (CPUE) of fished species in two ways: (1) Lionfish predation and competition with native species may lead to decreases in the target species population size (2) The presence of lionfish may increase the cost of fishing for other species in terms of time, effort, and safety risk. For example, lobster traps that are found with lionfish in them require extra time and effort in handling (Morris, 2012).

For tourism economies, lionfish could have an impact in two ways: (1) The invasion changes the ecosystem structure and makes it less desirable and attractive. For example, a reduction in coral reefs fishes and coral reefs themselves may affect dive tourism. (However, lionfish themselves are a popular sighting species and could actually boost tourism if divers find it desirable to fish for them. (2) In both cases there is increased risk to human health because of the possibility of envenomation of tourists (Morris, 2012).

4.1.6 Current Situation

Lionfish population density is 5 to 15 times denser in the Western Hemisphere than in the fish's natural range. It can sometimes reach 400 fish per hectare at sites off the coast of North Carolina and the Bahamas (Hoag, 2014). Across 17 locations off the coast of North Carolina in 2004 there was a reported average of 21 invasive lionfish per hectare (Hamner et al., 2007). In 2008, the highest lionfish densities reached was around 450 per hectare (off North Carolina) with mean densities of 150 per hectare (Morris, 2009).

It seems that lionfish will continue to expand southward to South America along the coastlines of the Caribbean until water temperature exceeds lionfish tolerance (Morris, 2009).

Figure 4.5: Potential Lionfish Future Distribution: Sea Surface Temperature is the Only Limiting Factor (Source: Morris, 2012)

4.2 Fishing Derbies and Dr.Stephanie Green's Work

4.2.1 Lionfish Derby in Key Largo, Florida

As an invasive-species management method, the fishing derby can be successful in managing lionfish densities and minimizing impacts on the local area. However, while local removal efforts can be effective in reducing targeted invasive species, time and geography are key to designing comprehensive control plans. The first step is identifying a priority area: a marine protected area

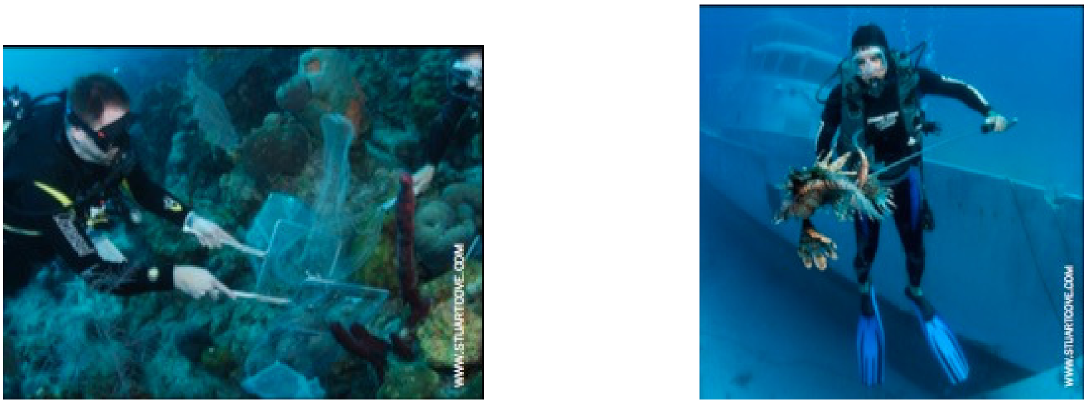
Gear type	User	Cost	Benefits	Limitations	Notes
Vinyl hand net	Divers and marine life collectors	Initial expense high	Highly effective for naive fish and smaller fish, when used properly does not scare fish.	Bulky to carry, fish must be accessible, successful use takes practice, slower captures.	
Mesh hand net	Divers and marine life collectors	Initial expense high	Effective for naive and smaller fish, when used properly does not scare fish.	Entanglement common, takes practice, slower captures.	
Plastic container (mask box, plastic bag)	Divers	Low	Commonly available.	Places user in close proximity to spines, only useful for very small fish.	
Polespear	Divers and spearfishers	Low	Effective for larger fish, rapid captures, keeps fish at distance from collector.	Misses are common, potential damage to resource, potential abuse, too large for most smaller fish.	Spearing devices may be prohibited or restricted in use to freediving only.
Hawaiian sling	Divers and spearfishers	Low	Effective for larger fish, rapid captures.	Spear leaves direct control of collector, misses are common, potential damage to resource, potential abuse, fish may slide toward collector, too large for most smaller fish.	Spearing devices may be prohibited or restricted in use to freediving only.
Speargun	Divers and spearfishers	High	Powerful enough for the largest fish.	Spear leaves direct control of collector, overkill for most lionfish, reloading and removal of fish is lengthy process.	Spearing devices may be prohibited or restricted in use to freediving only.
Specialty spearing devices	Divers and spearfishers	Varies, often high	Usually designed for ease of use, small enough to carry.	Depending on the device: may require two hands, may be shorter than traditional devices, may not secure fish following spearing, may require specialty parts for repair.	Specialty devices vary in their design and application. Spearing devices may be prohibited or restricted to freediving only.
Traps	Commercial fishers	Low	Already in use for other targeted species.	Bycatch is high.	Lionfish have been reported as common bycatch in some lobster and fish traps. However, no lionfish specific trap has yet been developed.
Hook and line	Commercial and recreational fishers	Low	Already in use for other targeted species.	Reported to be effective only in deepwater (300–600 ft), bycatch may be high.	Squid as cut-bait has been reported as successful lionfish bait.

Figure 4.6: Various Gear Types and Pros & Cons (Source: Morris, 2012)

(MPA), high visitation or tourism spot, spawning aggregation areas, vulnerable nursery sites, or other high priority areas (Morris, 2012). The presence of divers or tourists who enjoy diving and snorkeling make it possible for lionfish removal to become a part of the tourism trade and a boon to a local economy (Morris, 2012).

In the Key Largo derby, lionfish hunting weapons are restricted to nets and spears, thus standardizing the fishing efforts from one team to another. (The use of hand-held nets is standard for divers whose primary means of hunting is spear fishing.) Because the lionfish is sedentary while waiting patiently for prey to cross its path, the most effective way to hunt lionfish is to stalk them and pierce their skin with a spear fishing gun at close range (Morris, 2012).

Lionfish derbies in Florida often raise significant prize money through spon-



(a) Small Mesh Bait Nets (b) Hawaiian Sling

Figure 4.7: Major Lionfish Fishing Tools (Source: Morris, 2012)

sorships and reward winners handsomely. With good reason: In 2009, the 18 teams in the lionfish derby in Abaco, Bahamas, helped to remove 1,408 lionfish in a single day.

In addition to encouraging local tourism, the derbies help scientific institutions to collect data. They also educate the public about the fish by, among other things, offering lionfish tastings.

The main initiatives for managing lionfish derbies are nonprofit organizations, park managers, fishermens' unions, and research institutions (Cote, 2014). According to REEF data, prize money remains at approximately \$3,550 (in total) each year from 2010 to 2016, except in 2013 when the the prize was slightly more, \$3,625.

4.2.2 Dr. Stephanie Green's Study

In a study of the ecological effects of invaders, Dr. Stephanie Green et al. (2014) constructed an ecological model to find the threshold density of suppressing

Figure 4.8: Lionfish Derby in the Green Turtle Cay, Abaco, Bahamas, 2009 (Source: Morris, 2012)

lionfish based on the hypothesis that the biomass of prey fishes left on a reef will decline if lionfish consume prey at a rate that exceeds the rate of prey production. The study then calculated two rates (prey consumption by invasive lionfish and biomass production by native fish prey) for experimental reefs and manipulated lionfish densities to observe changes of prey species biomass. The targeted threshold for suppressing lionfish densities would be those reefs where prey species biomass had minimal changes (Green et al., 2014).

Dr. Green's study was conducted over 18 months on 24 natural coral patch reefs in Rock Sound, off Eleuthera Island, Bahamas, between December 2009 and June 2011 (Green et al., 2014).

By experimentally adjusting lionfish densities for each reef to approach the simulated threshold, and monitoring native fish populations, the researchers tested their predictions (Green et al., 2014). They finally predicted that for some reefs it was necessary to remove 25-92% of lionfish to prevent the animals from consuming too much prey. After the experiment, they found native species had rebounded by 50-70% in the reef that reached targeted protection goal (Hoag, 2014; Green et al., 2014).

In a paper under peer review, Dr. Green describes in detail how the derbies proceeded in Key Largo, Florida, between 2012 and 2014. Lionfish densities were reduced by an average of 52% over the 192 km^2 competition area in the Bahamas and Florida. The research team's before-and-after control impact field surveys (BACI) helped to estimate initial lionfish densities in derby area; this is an important data reference for this thesis.

The data for Dr. Green's research was randomly selected from 60 survey sites that ranged from less than a km from the central scoring station to more than 50km away. The 60 sites included a variety of near-shore marine habitats, such as patch coral reefs, artificial structures, sea grass beds, and shoreline ledges at depths of 5 to 15 ft. This assortment of habitats covered lionfish habitats that were likely to be culled in a derby and those that were unlikely to be culled. By conducting detailed research on each site one week prior to the derby and one week after the derby, Dr. Green estimated the pre- and post-derby lionfish densities from 2012 to 2014 (Green et al., Unpublished).

She found that derby participants helped to reduce an average of 57% lionfish densities within the derby-designated areas. Population suppression did not appear to affect the areas adjacent to the derby areas. Lionfish size increased over time on Florida habitats that total invader biomass rebounded to pre-culled levels after each derby. Dr. Green summarizes three potential reasons for lionfish recolonization rates: (1) Lionfish population in Key Largo, Florida is in a stage in their trajectory of population quick increase. (2) High-complexity coral patch reefs and artificial structures provide lionfish food and rest resources. (3) Movement of adult lionfish from adjacent habitats has important impacts in colonization (Green et al., Unpublished).

4.3 Environmental Costs of Lionfish

The Reef Environmental Education Foundation (REEF) has been holding annual lionfish fishing derbies in Key Largo since 2010. In 2013, a total of 22 teams with a maximum of four members each caught 707 lionfish . This was the year that \$3,625 was awarded in prize money. Based on 50 completed surveys returned from participants, the investigated group included people of all ages and an even mix of local residents and out-of-towners. This survey also showed that most of the participating lionfish hunters are high-income earners which may indicate a willingness to participate in future derbies. Participants spent a total of \$24,561 for this single-day derby event (or approximately \$280 per person). Their main expenditures were boat fuel (16%), dive boat fees (14%), accommodations, restaurant meals, and automobile transport (12% each), according to Nardelli et al. (2014).

An alternative method to estimate the environmental costs caused by lionfish uses a travel cost model or contingent valuation method. However, since there is not enough data to conduct these two econometric analyses, a list of invasive species in south Florida can be helpful. There are more than 29 non-indigenous species, according to the USGA website. A list is in Appendix.

CHAPTER 5

ECONOMETRIC ANALYSIS

5.1 Data Collection

Lionfish derbies have been held in Key Largo, Florida, since 2010, and there are seven derbies for which information has been recorded by organizers and volunteers. Two main sources of data include: primary data from these seven derbies between 2010 and 2016 as collected by derby participants and REEF organizers; and secondary data from Dr. Stephanie Green at Oregon State University. We thank Dr. Green for her willingness to share her data.

REEF's data includes: (1) the length of each lionfish caught in each of the derbies, (2) the number of teams each year, (3) the prize monies awarded, and (4) number of lionfish caught. Dr. Green's data includes lionfish population estimates for 60 randomly selected sites ranging from 1 km to 50 km from the central scoring station, one week before and one week after each derby (both percentage change and numbers for the derby area). These 60 sites covered a variety of near-shore marine habitats, including: (1) patch coral reefs, (2) artificial structures, (3) sea grass beds, and (4) shoreline ledges at depths of 5 to 15 ft. Before and after comparisons allowed Dr. Green to estimate the reduction in lionfish density attributable to each derby (Green et al., Unpublished).

The data covers only seven derbies and is therefore of limited use in the calibration of certain bioeconomic parameters needed for our model. Thus we calibrated some parameters from extrapolations of the biological literature on lionfish and from plausible, subjective judgments. The data pertains only to

Key Largo. Derbies are always affected by a variety of ecological and sociological factors and each one exhibits different data. The lionfish derby data in this analysis only represents one location's use of the derby as an invasive-species management tool.

Our analysis determines the optimal amount of prize money that should be awarded for maximum effect in lionfish derbies in Key Largo. We conduct a sensitivity analysis to determine how this amount is affected by a change in each bioeconomic parameter. Scientists first spotted lionfish in Key Largo in 2009, the first derby was held in 2010, and the most recent derby was in September 2016.

REEF's data includes the length of every lionfish taken during seven years of derbies. We use a known metabolic relationship that relates biomass of the ith lionfish, B_i in grams, to length, L_i in centimeters (Allen, 1971; Banse et al., 1980; Jennings, 2015).

$$B_i = a_1 L_i^{b_1} \tag{5.1}$$

where $a_1 = 0.00497$ and $b_1 = 3.291$ are length to mass scaling constants found at fishbase.org. We can then calculate total harvest biomass for each year. Total prize money each year was \$3,550, with the exception of 2013 when it was \$3,625. For our analysis, it would have been helpful if the prize money had varied (between \$1,000 and \$20,000 for example) to see if the size of the prize influenced the number of participants and to determine the optimal prize. Table 5.1 displays data on total catch, fish length, fish biomass, effort (number of participating teams and prize money from 2010 to 2016). Note that taking 2010 as the base year, all award prizes are adjusted to be in 2010 dollars. Data on the fishing area and percentage of biomass reduction are reprinted in Table 5.2.

5.2 Empirical Strategy

5.2.1 Parameters

Some of our parameters come from the literature and from scientific websites; whereas some other parameters are calibrated from assumptions.

Since there are few studies of lionfish ecology in the Gulf of Mexico or Florida Keys, the carrying capacity K is unknown. I assume it is greater than any lionfish densities measured before derbies:

$$K \geq x_t^B, t\ is\ from\ 2012\ to\ 2014$$

The intrinsic growth rate of red lionfish in the southern Gulf of Mexico is r = 0.88 (Source: Fishbase.org). It is estimated from the von Bertalanffy growth function (VBGF):

$$l_t = l_\infty(1 - e^{-K(t-t_0)})$$

(Note that K is growth rate in this function, not carrying capacity.)

The construction of the harvest function employs the Cobb Douglas model

Table 5.1: Lionfish Derby Summary Statistics from 2010 to 2016

	2010	2011	2012	2013	2014	2015	2016
Total Catch (#)	532	675	461	707	573	488	323
Average Length (mm)	139.77 (25.464)	197.4 (44.090)	194.07 (66.785)	219.37 (68.141)	262.32 (61.87)	256.68 (66.864)	255.85 (68.528)
Min (mm)	50	70	43	42	51	24	48
Max (mm)	270	373	410	426	435	433	414
Average Biomass (g)	32.92 (21.462)	109.04 (85.745)	127.63 (145.185)	177.23 (170.491)	280.07 (203.885)	270.13 (207.515)	270.58 (211.308)
Min (g)	0.992	3.003	0.604	0.559	1.059	0.089	0.868
Max (g)	255.255	739.350	1,009.318	1,144.836	1,226.379	1,207.920	1,042.088
Team Numbers (#)	21	16	9	22	15	14	9
Total Prize Award ($)	3,550	3,441.37	3,371.6	3,322.93	3,669.88	3,266.01	3,207.33

[a] Source: Reef Environmental Education Foundation.

[b] Standard deviations in parentheses

[c] 2010 as base year. Based on latest US Government CPI data, prize and cost need to be adjusted for inflation effects

Table 5.2: Lionfish Derby Summary Statistics from 2010 to 2016 (cont'd)

	2010	2011	2012	2013	2014	2015	2016
Area Fished (km^2)	-	-	218	207	194	-	-
Percentage density reduction ($fish * ha^{-1}$)	-	-	59	74	23	-	-
Percentage biomass reduction ($kg * ha^{-1}$)	-	-	60	76	11	-	-

[a] Source: Dr Green (Reviewing), Table 1.

with Ordinary Least Square estimation procedures. The general idea is to see how changes in prize money affect total harvest of lionfish biomass in year t. With this objective in mind, I perform three steps to calibrate unknown parameters or estimate biomass, including congestion parameters and harvest function coefficients. We perform different regressions on lionfish derby information and on Dr. Green's data.

Step one uses lionfish derby harvest information and Dr. Green's study of the percentage of lionfish reduction to calculate pre-derby lionfish biomass for years 2012, 2013, and 2014. The mathematical relation can be stated as:

$$
\begin{aligned}
Total\ Harvest\ Biomass_t &= Total\ Catch_t \ * \ Average\ Biomass_t \\
&= \%\ Biomass\ Reduction_t \ * \ Pre - Derby\ Biomass_t \\
Pre - Derby\ Biomass_t &= \frac{Total\ Catch_t \ * \ Average\ Biomass_t}{\%\ Biomass\ Reduction_t}
\end{aligned}
$$

Table 5.3: Reprint Lionfish Derby Summary Statistics from 2010 to 2016

	Pre-derby biomass: x_t (g)	Total Harvest Biomass: h_t (g)	Team Numbers: N_t (#)	Total Prize Award: p_t ($)
2010	-	17,515.65	21	3,550.00
2011	-	73,600.39	16	3,441.37
2012	98,059.00	58,835.40	9	3,371.60
2013	164,873.37	125,303.76	22	3,322.93
2014	1,458,910.09	160,480.11	15	3,269.88
2015	-	131,823.67	14	3,266.01
2016	-	87,396.77	9	3,207.33

[a] Source: Reef Environmental Education Foundation and Dr Green (Reviewing), Table 1, p. 18

In step two, I use participants' information and prize money to estimate congestion parameter β. The regression is:

$$N_t = p_t^{\beta}$$
$$lnN_t = \beta ln p_t$$

where N_t is the number of teams in year t and p_t is the total award prize money in year t.

In step three, I use derby harvest information, calculate pre-derby biomass and the number of participating teams, and then estimate the coefficient of harvest function. Based on our assumption, the harvest function is:

$$h_t = mN_t x_t$$
$$m = \frac{h_t}{x_t N_t} \; t = 2012,\ 2013,\ 2014$$

where h_t is total harvested biomass in year t. N_t is the number of participating teams in year t. x_t is the calculated pre-derby biomass (g) in year t (t = 2012, 2013, 2014).

The lionfish environmental cost function is density dependent, and I assume that

$$D = \frac{d}{2} x_t^2$$

where d is the environmental damage coefficient. Since a travel cost model and contingent valuation method are not available here to do an estimation, I may just make some assumptions for lionfish environmental damages and use it to calculate damage coefficient d.

5.2.2 Threshold x^* and p^*

The Excel solver can help to find an optimal solution but it locates only the *local* minimum optimal solution, not the *global* optimal solution.

Instead, I use the $x^* - p^*$ table to identify the optimal combination. As we can see in Table 5.3, the first row represents varied award prizes from \$0 to \$12,000 in \$400 increments. The first column represents designed lionfish biomass from 500,000 to 1,900,000. Each cell is a calculated cost of different combinations. These are then sorted for the minimum value for each threshold of lionfish biomass in the last column. In other words, each row is an attempt to find the minimum cost for a specific designed lionfish biomass threshold x^*. After locating each row's minimum costs in the table, the corresponding award prize p^* can be decided. The combination $[x^*, p^*]$ is then the threshold with a specific total cost. Table 5.4 is a frame of table method.

5.2.3 Sensitivity Analysis

Sensitivity analysis measures the reaction of a model to small changes in parameters, whether these are identified in the literature or come from estimation strategies. The more accurately they are defined, the more reliable the model and its ability to forecast the evolution of the system under different conditions.

Table 5.4: Table Method Finding Threshold [x^*, p^*]

x^* \ p^*	0	\$400	.....	\$11,600	\$12,000	Min TC
500,000			.....			
600,000			.....			
.....	.....	.....	.....	.....	.....	.....
1,800,000			.....			
1,900,000			.....			

The method is to change the parameters that are not estimated by econometric techniques to conduct sensitivity analysis: carrying capacity, discount rate, and environmental damage coefficient (Link et al., 2011; Dueri et al., 2012). To be more explicit, the base case for carrying capacity is $K = 2,000,000\ g$. By changing carrying capacity (K) by 10% every time and then calculating the threshold award prize, we find that the total cost is the same for the designed threshold of lionfish derby biomass $x^* = 1,000,000\ g$. The same idea also applies to discount rate (δ) and environmental damage coefficient (d), but it is not necessary to change 10% each time.

By comparing percentage change of parameters with percentage change of corresponding threshold prizes and total cost, I calculate the elasticity to show optimal prizes and total cost responsiveness to those parameters.

The responsiveness of award prize can be expressed as

$$\frac{\Delta p^*/p^*}{\Delta K/K} \quad and \quad \frac{\Delta TC/TC}{\Delta K/K} \tag{5.2}$$

Similarly, responsiveness of discount rate and environmental damage coefficient can then be:

$$\frac{\Delta p^*/p^*}{\Delta \delta/\delta} \quad and \quad \frac{\Delta TC/TC}{\Delta \delta/\delta} \tag{5.3}$$

$$\frac{\Delta p^*/p^*}{\Delta d/d} \quad and \quad \frac{\Delta TC/TC}{\Delta d/d} \tag{5.4}$$

5.3 Results

5.3.1 Descriptive Statistics

In Figure 5.1 and Figure 5.2, I present the time series trend and histogram of lionfish derbies from 2010 to 2016. This reveals several significant characteristics of our sample. The average length and biomass of lionfish caught by participants increased from 2010 to 2014, when it reached a height of 262.73 mm and 280.07 g; it then decreased to approximately 255 mm and 270 g in years 2015 and 2016. The increase in length and biomass from 2010 to 2014 suggested the possibility that lionfish density was increasing. Figure 5.1 shows that standard deviation in length grew rapidly before 2012, then grew flatter from 2012 to 2016. The standard deviation for biomass increased at a decreasing rate from 2010 to 2016. Although biomass has increased over the years, the decreasing rate and stable standard deviation in length is a sign that the lionfish population in Key Largo may have reached a relatively stable state.

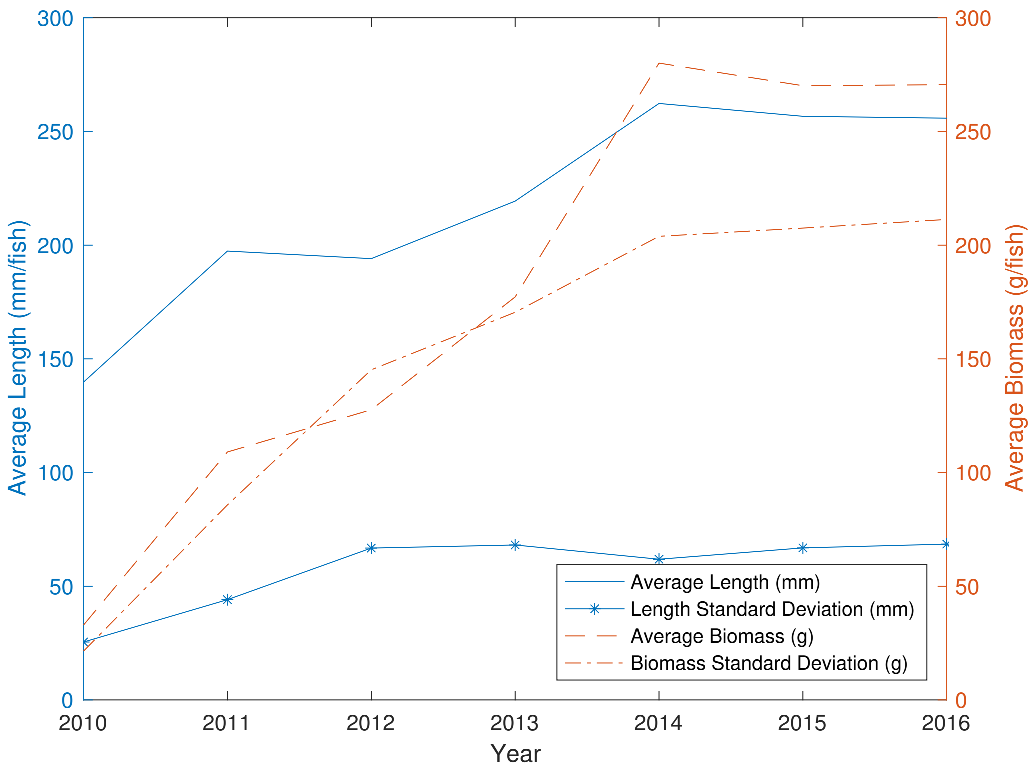


Figure 5.1: Length (mm), Biomass(g), Length Standard Deviation (mm) and Biomass Standard Deviation (g)

Figure 5.2 reflects the distribution of lionfish sizes with a 95% confidence interval for each derby. The average length was moving rightward and 95% range dispersed at first and became more stable from 2012 to 2016.

There are various factors that affect lionfish biomass. The Key Largo derby may be an important one in reducing and lionfish density to a relatively stable level. Dr. Green's study suggests that adult lionfish from adjacent habitats may be the reason for the increased size over time (Green et al., Unpublished).

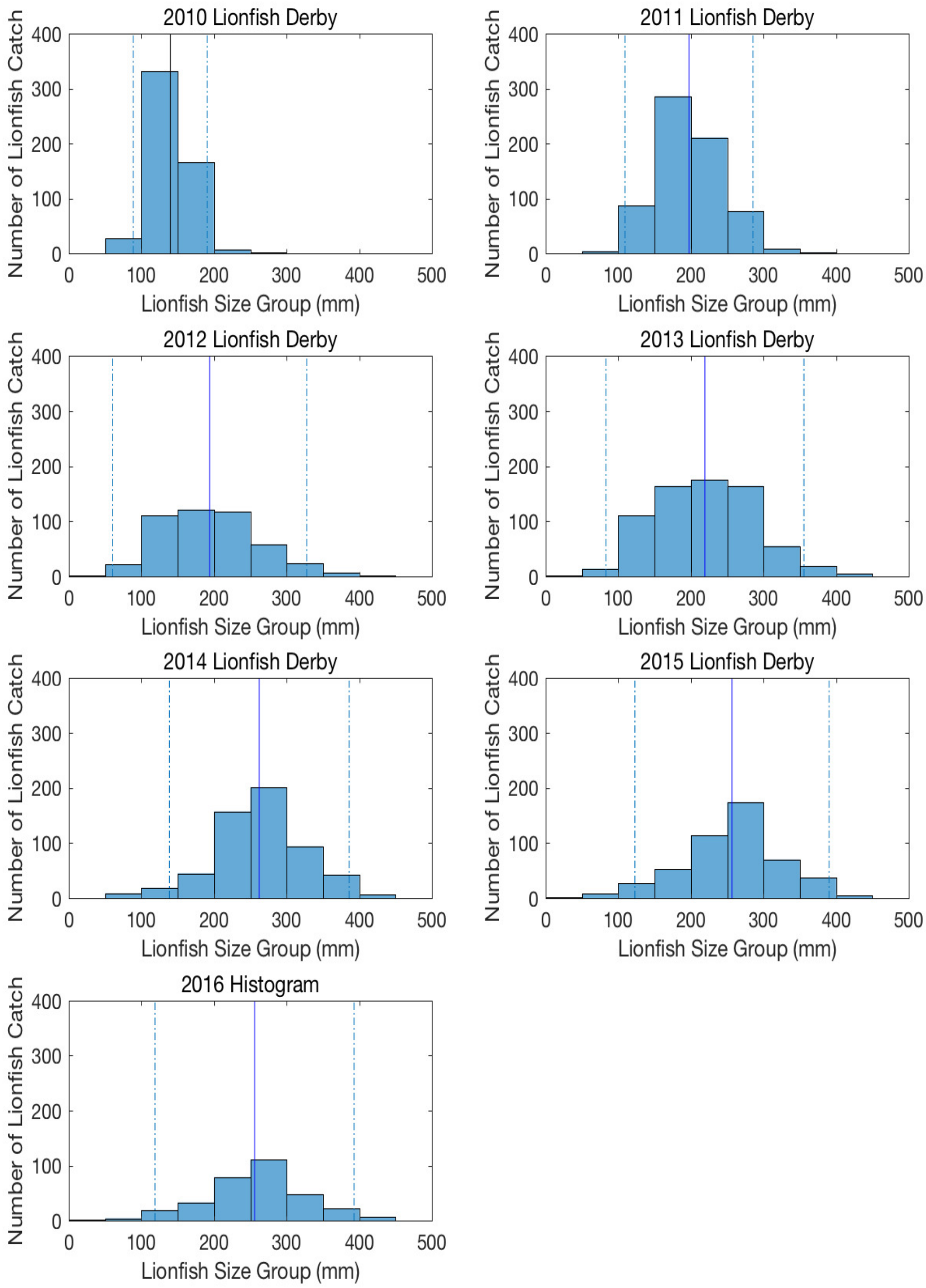


Figure 5.2: Histogram Lionfish Derby

5.3.2 Parametrization and Initial Guess

In order to calculate the threshold for lionfish densities and optimal prize money for fishing tournaments, there are several parameters to be calibrated based on our model and assumptions.

Intrinsic Growth Rate r

The intrinsic growth rate of lionfish was measured to be $r = 0.88$ in Alacranes Reef, located in the southern Gulf of Mexico (Source: fishbase.org). This growth rate is estimated from the von Bertalanffy growth function (VBGF):

$$l_t = l_\infty(1 - e^{-K(t-t_0)})$$

(Note that K is growth rate in this function, not carrying capacity.)

Discount Rate δ and Initial Stock x_0

Let's take discount rate $\delta = 0.02$ and initial lionfish biomass $x_0 = 100,000$ g.

Environmental Carrying Capacity K

Dr. Green measured the percentage of biomass reduction pre- and post- derby from 2012 to 2014. This information provides clues to calculate local pre-derby lionfish densities for three consecutive years. For example, an estimated 60%

reduction in biomass in year 2012 within the 218 km^2 derby area means that the total harvest of lionfish in the 2012 derby was just equal to 60% of pre-derby lionfish biomass. Similarly, pre-derby lionfish biomass can also be calculated for the 2013 and 2014 derbies. Thus,

$$
\begin{aligned}
Total\ Harvest\ Biomass_t &= Total\ Catch_t \ * \ Average\ Biomass_t \\
&= \%\ Biomass\ Reduction_t \ * \ Pre - Derby\ Biomass_t \\
THB_{2012} &= 0.6x^B_{2012} = 58,835.40\ g,\ x^B_{2012} = 98,059.00\ g \\
THB_{2013} &= 0.76x^B_{2013} = 125,303.76\ g,\ x^B_{2013} = 160,480.11\ g \\
THB_{2014} &= 0.11x^B_{2014} = 159,526.90\ g,\ x^B_{2014} = 1,458,910.09\ g
\end{aligned}
$$

As for the carrying capacity K in Key Largo, there are few studies of it. From Figure 5.1 and Figure 5.2, the harvested lionfish's average length and biomass reached their highest levels in 2014. By calculating three consecutive years' pre-derby lionfish biomass (2012 to 2014), I assume the carrying capacity is greater than the highest pre-derby biomass densities and that $K = 2,000,000\ g$.

Congestion Parameter β

A direct measure of congestion parameter β and harvest function coefficient m is unavailable. However, a simple assumption can be made that the number of participating teams is an exponential function of total prize money to congestion parameter $0 < \beta < 1$ with the coefficient set to 1.

Although the prize money has been adjusted for inflation, the dataset is so

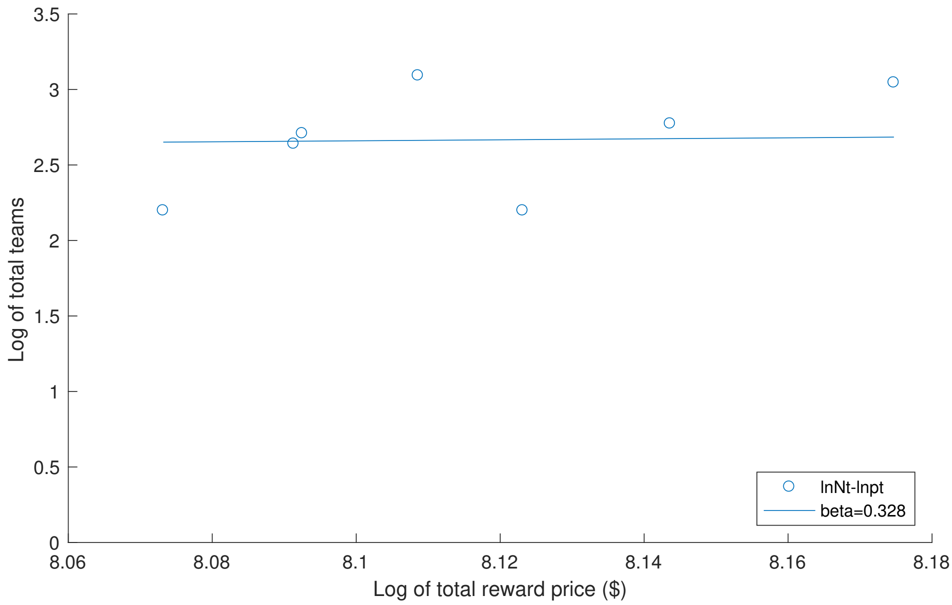


Figure 5.3: Participating Team as a Function of Prizes

small that I get an initial guess of β by conducting Ordinary Least Square estimation.

Table 5.5 presents the OLS estimates of the effect of prize money on participating teams. It shows that the congestion parameter β is 0.328 with p value less than 0.05. The estimate in Table 5.5 is therefore consistent with the hypothesis.

Harvest Function Coefficient m

There are only three observations and the estimation result is an initial guess.

Table 5.6 shows OLS estimates of the product of participating teams and the pre-derby biomass on total harvest of lionfish biomass. The coefficient m is 0.00816, but p value is greater than 0.05, which is insignificant. Since there are

Table 5.5: OLS Estimates of the Effect of Derby Prize Money on Number of Participating Teams. Dependent Variable: Log of Participating Teams. Independent Variable: Log of Prizes, 2010 to 2016

Variable	**Coefficient**	**(Std. Err.)**
lnpt	0.328***	(0.016)
N	7	
R^2	0.985	
Adj-R^2	0.983	
$F_{(1,6)}$	396.194	

*** $p < 0.001$.

Table 5.6: OLS Estimates of the Effect of Product of Participating Teams and Pre-derby Lionfish Biomass on Total Harvest of Lionfish Biomass. Dependent Variable: Participating Teams × Pre-derby Biomass. Independent Variable: Total Harvest Biomass, 2012 to 2014

Variable	**Coefficient**	**(Std. Err.)**
$N_t x_t$	0.00815	(0.004)
N	3	
R^2	0.729	
Adj-R^2	0.594	
$F_{(1,2)}$	5.39	

$p > 0.05$

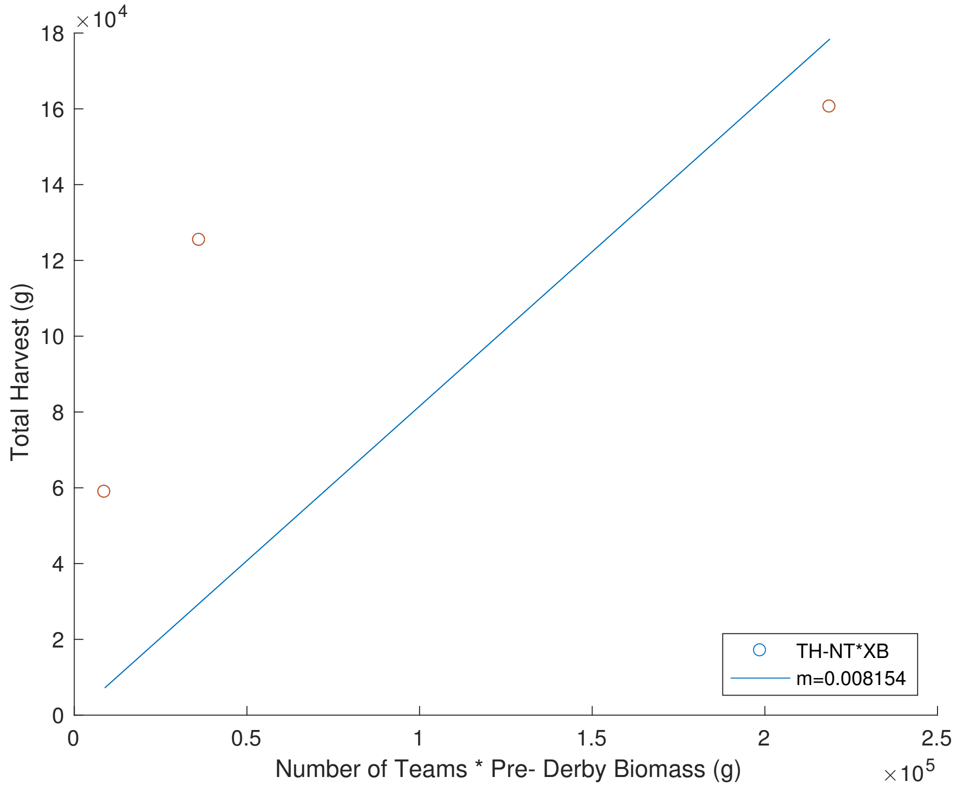


Figure 5.4: Harvest Function

only three observations for conducting this OLS estimation, it is an initial guess for sensitivity analysis.

Environmental Damage Coefficient d

Environmental costs are a big part of each derby's total costs. Since there is not enough information on the participants themselves, it is not possible to use the contingent value method or travel costs model to estimate the environmental costs of the event. Instead, the environmental damages are assumed to be \$0.02/ha. Taking the average derby area to be 200 km^2 and lionfish biomass to have a maximum carrying capacity such that $x_t = K = 2,000,000$ g, then $x_t = 10,000\ g/km^2$. Based on

$$
\begin{aligned}
D &= \frac{d}{2}x_t^2 \\
d &= \frac{2D}{x_t^2} \\
&= 0.00000004
\end{aligned}
$$

Notice that I made several assumptions for calculating parameters that doesn't reflect the real situation. However, I can vary values for d to see how threshold x^* and p^* and optimization lionfish densities changes over time.

The initial guess for all parameters are listed in Table 5.7.

Table 5.7: Initial Guess

Parameter	Meaning	Value
Biological Parameters		
r	Intrinsic growth rate	0.88
K	Carrying capacity	2,000,000
Economic Parameters		
β	Congestion parameter	0.328
δ	Discount rate	0.02
d	Damage coefficient	0.00000004
m	Harvest function coefficient	0.00815
Initial Conditions		
x_0	Initial value of lionfish population density at t=0	100,000

5.3.3 Threshold x^* and p^*

In our model, the threshold combination $[x^*, p^*]$ can be understood to mean that if lionfish density in Key Largo near the shore where the derby will be held is greater than the invasive-species manager's designed threshold x^* , then the derby should be held and winners awarded p^* prize.

The threshold range for lionfish biomass and award prize is x^* from 100,000 g to 2,000,000 g and p^* is from 0 to \$12,000. In Figure 5.5, we can see from the 3D plot that total costs over the years increases when the threshold of lionfish biomass is increasing; and it is generally increasing when the threshold derby prize is decreasing. However, it cannot be known directly from the figure whether the total cost will increase or decrease as the prize money keeps going up.

In Figure 5.6, different colored lines represent different prize levels p^*. There are two features of the increasing trend: (1) For $p^* = 0$, the highest blue line has constant total costs of approximately \$3.1 million. All other colored lines represent the total cost for other prize money. They are all lower than the blue line. This means that the total costs in a year that has a lionfish derby is always lower than the total costs in a year in which the lionfish derby is not held. (2) For each prize, the total cost increases when threshold biomass increases generally.

In Figure 5.7, different colored lines represent different thresholds of lionfish biomass x^*. The highest yellow line represents the threshold of biomass equal to the environmental carrying capacity $x^* = K = 2,000,000$. In that situation, total costs will be approximately \$3.1 million. For other threshold biomass, total cost is decreasing when the prize is increasing, and after reaching a level then the

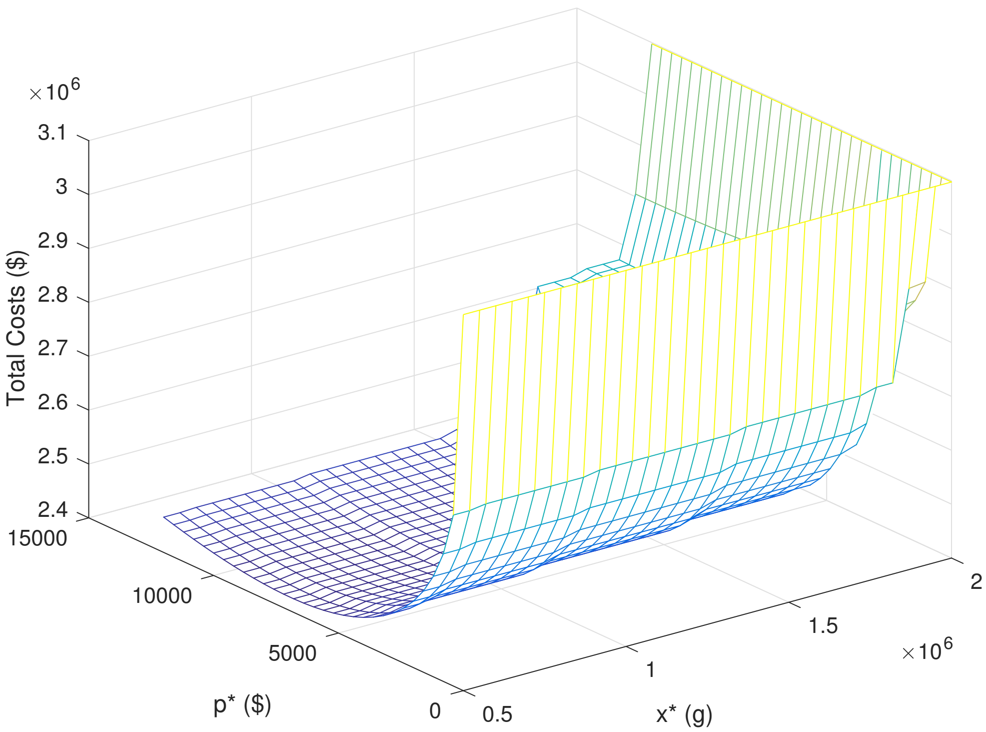


Figure 5.5: Total Costs with Different Combination of Threshold Lionfish Biomass and award Prize $[x^*, p^*]$

total cost increases.

Returning to Figure 5.5, the exact optimal combination of x^* and p^* from the graph may not be located directly; but there is an alternative way to do this. By using the table method shown in Table 5.4, all optimal combinations are listed in Table 5.10. Table 5.8 and Table 5.9 are excerpts of the table method that calculates total costs for lionfish biomass from $500,000$g to $1,900,000$g and award prize p^* from 0 to $\$12,000$. Then it also helps to locate the approximate threshold $[x^*, p^*]$ combination that leads to minimum total costs for each different lionfish biomass threshold x^* level. For example, in the first row of Table 5.8 and Table

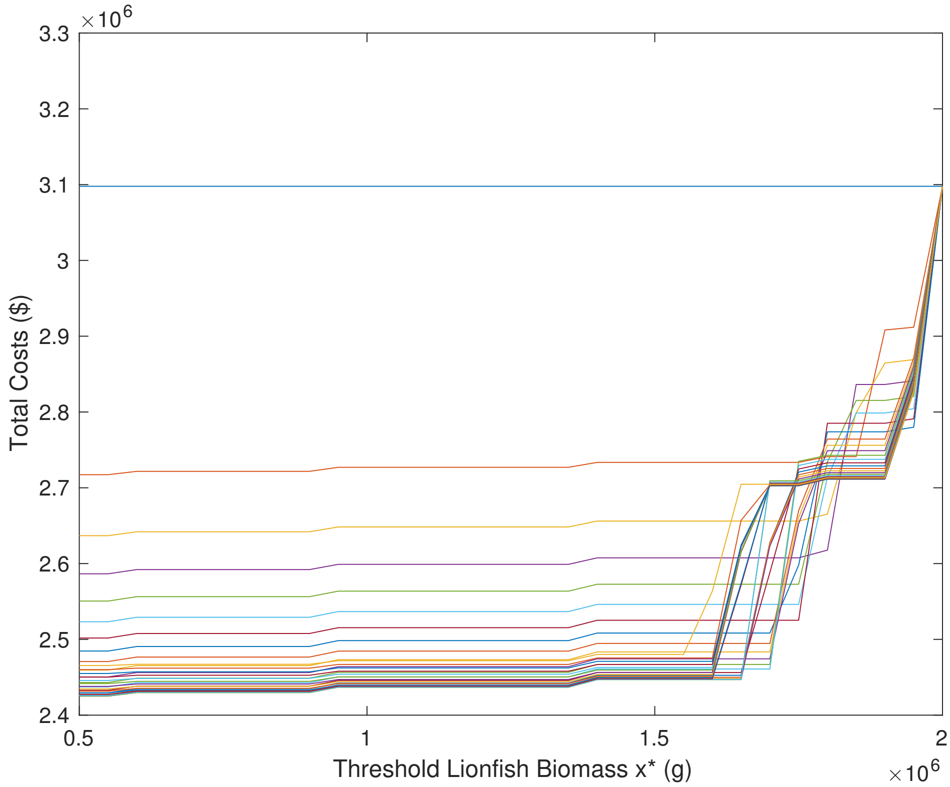


Figure 5.6: Total Costs with Different Thresholds of Lionfish Biomass x^*

5.9, each cell calculates total costs of $x^* = 500,000$ and $p^* \in [0,\ 400,\ .....\ , 12000]$, then the last column indicates that the minimum costs for $x^* = 500,000$ is $2,425,146.52. This is the value when $p^* = 6,800$ (Underline Value). Thus, [x^*,p^*]=[500000, 6800] is the optimal threshold combination with minimum costs equal to $2,425,146.52. Similarly, all other optimal threshold combinations can be located. Note that the table method helps to locate the approximate combination of optimal threshold p^*, we then need to use a spreadsheet and Excel Solver to double check the p^* and find a more accurate p^* value for each x^* and total costs.

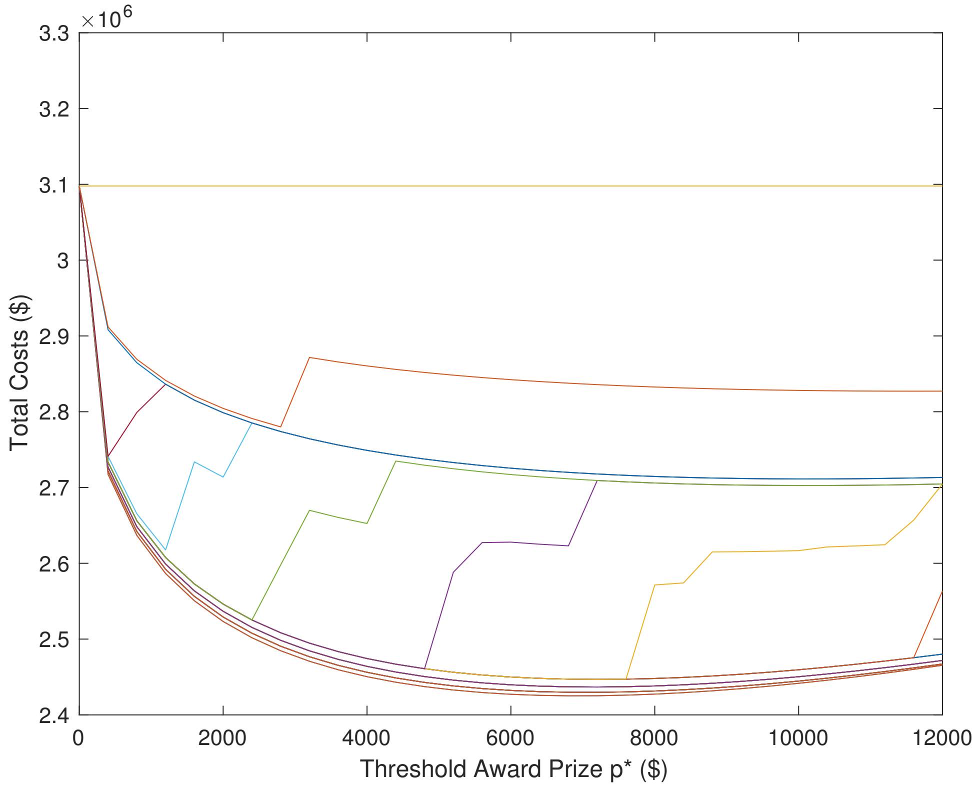


Figure 5.7: Total Costs with Different Thresholds of Lionfish Prizes p^*

Table 5.8: Excerpt of Table Method Finding Threshold Combination [x^*, p^*]

x^* \ p^*	0	…..	1,200	…..	4,800	…..	6,800	minTC
500,000	3,097,796.21	…..	2,586,518.73	…..	2,437,297.90	…..	2,425,146.52	2,425,146.52
600,000	3,097,796.21	…..	2,592,080.20	…..	2,442,845.28	…..	2,429,852.22	2,429,763.91
700,000	3,097,796.21	…..	2,592,080.20	…..	2,442,845.28	…..	2,429,852.22	2,429,763.91
800,000	3,097,796.21	…..	2,592,080.20	…..	2,442,845.28	…..	2,429,852.22	2,429,763.91
900,000	3,097,796.21	…..	2,592,080.20	…..	2,442,845.28	…..	2,429,852.22	2,429,763.91
1,000,000	3,097,796.21	…..	2,598,991.00	…..	2,450,557.15	…..	2,437,004.82	2,436,768.81
1,100,000	3,097,796.21	…..	2,598,991.00	…..	2,450,557.15	…..	2,437,004.82	2,436,768.81
1,200,000	3,097,796.21	…..	2,598,991.00	…..	2,450,557.15	…..	2,437,004.82	2,436,768.81
1,300,000	3,097,796.21	…..	2,598,991.00	…..	2,450,557.15	…..	2,437,004.82	2,436,768.81
1,400,000	3,097,796.21	…..	2,607,577.60	…..	2,460,931.65	…..	2,447,156.53	2,446,832.43
1,500,000	3,097,796.21	…..	2,607,577.60	…..	2,460,931.65	…..	2,447,156.53	2,446,832.43
1,600,000	3,097,796.21	…..	2,607,577.60	…..	2,460,931.65	…..	2,447,156.53	2,446,832.43
1,700,000	3,097,796.21	…..	2,607,577.60	…..	2,460,931.65	…..	2,623,029.17	2,460,931.65
1,800,000	3,097,796.21	…..	2,617,714.31	…..	2,737,553.60	…..	2,719,970.66	2,617,714.31
1,900,000	3,097,796.21	…..	2,836,300.89	…..	2,737,553.60	…..	2,719,970.66	2,711,319.98

Table 5.9: Excerpt of Table Method Finding Threshold Combination [x^*, p^*] (cont'd)

x^* \ p^*	7,200	.....	10,000	.....	12,000	minTC
500,000	2,425,256.21	.....	2,441,664.59	.....	2,465,463.00	2,425,146.52
600,000	2,429,763.91	.....	2,444,604.54	.....	2,467,143.28	2,429,763.91
700,000	2,429,763.91	.....	2,444,604.54	.....	2,467,143.28	2,429,763.91
800,000	2,429,763.91	.....	2,444,604.54	.....	2,467,143.28	2,429,763.91
900,000	2,429,763.91	.....	2,444,604.54	.....	2,467,143.28	2,429,763.91
1,000,000	2,436,768.81	.....	2,450,355.34	.....	2,471,828.68	2,436,768.81
1,100,000	2,436,768.81	.....	2,450,355.34	.....	2,471,828.68	2,436,768.81
1,200,000	2,436,768.81	.....	2,450,355.34	.....	2,471,828.68	2,436,768.81
1,300,000	2,436,768.81	.....	2,450,355.34	.....	2,471,828.68	2,436,768.81
1,400,000	2,446,832.43	.....	2,459,534.65	.....	2,480,169.89	2,446,832.43
1,500,000	2,446,832.43	.....	2,459,534.65	.....	2,480,169.89	2,446,832.43
1,600,000	2,446,832.43	.....	2,459,534.65	.....	2,563,578.62	2,446,832.43
1,700,000	2,709,286.71	.....	2,702,613.06	.....	2,704,632.45	2,460,931.65
1,800,000	2,717,823.63	.....	2,711,319.98	.....	2,713,317.62	2,617,714.31
1,900,000	2,717,823.63	.....	2,711,319.98	.....	2,713,317.62	2,711,319.98

Table 5.10: Threshold Biomass and Prize Combination

x^* (g)	p^* ($)	Cmin ($)	Periodic Derbies	1st Derby Start Year	Sustained Lionfish Biomass Level (g)
500,000	$6,935.23	$2,425,106.05	No	4th	1,663,044.193
600,000	$7,050.54	$2,429,717.49	No	5th	1,661,216.819
700,000	$7,050.54	$2,429,717.49	No	5th	1,661,216.819
800,000	$7,050.54	$2,429,717.49	No	5th	1,661,216.819
900,000	$7,050.54	$2,429,717.49	No	5th	1,661,216.819
1,000,000	$7,141.35	$2,436,762.00	No	6th	1,659,791.722
1,100,000	$7,141.35	$2,436,762.00	No	6th	1,659,791.722
1,200,000	$7,141.35	$2,436,762.00	No	6th	1,659,791.722
1,300,000	$7,141.35	$2,436,762.00	No	6th	1,659,791.722
1,400,000	$7,199.62	$2,446,832.00	No	7th	1,658,883.7
1,500,000	$7,199.62	$2,446,832.00	No	7th	1,658,883.7
1,600,000	$7,199.62	$2,446,832.00	No	7th	1,658,883.7
1,700,000	$4,866.81	$2,460,062.42	No	7th	1,700,000.112
1,800,000	$1,413.78	$2,598,228.97	No	8th	1,800,000.003
1,900,000	$10,130.88	$2,711,309.00	Yes	8th	1,664,990.116

[a] The Reference Discount Rate $\delta = 0.02$.

[b] The Reference Carrying Capacity is $K = 2,000,000$.

[c] Sustained Lionfish Biomass Level for $x^* = 1,900,000$ is obtained in year with derby.

Table 5.10 presents the corresponding results for the threshold biomass from $500,000$ g to $1,900,000$ g. The first column lists different lionfish biomasses in increments of $100,000$ g. Using the table method, the corresponding threshold prize and minimum environmental costs are presented in columns two and three. Column four indicates whether a derby is periodical: An entry of 'No' means the lionfish derby will be held every year while 'Yes' means that a derby will be held every other year. Column five indicates the anniversary of the first year of the derby. Column six is the final sustained lionfish biomass after the derby has been held for several years.

Table 5.10 shows several interesting features. For each specific lionfish biomass, there is a corresponding prize. Although some of the designated biomass amounts have the same prizes with the same calculated minimum total cost, it can be observed from the table that in general the minimum total costs increases when the designated threshold increases. However, p^* is not always increasing as x^* is increasing: When x^*= 1,700,000 g, C_{min}= \$2,460,062.42 is greater than the previous value, but p^*= \$4,866.81.73 is decreasing. When x^*= 1,800,000 g, C_{min}= \$2,598,228.97 keeps on increasing, but p^*= \$1,413.73, which is lower than all previous p^* levels. All lionfish levels will be held every year except lionfish biomass threshold x^*= 1,900,000 g. The very first year of the lionfish derby is delayed generally when the threshold biomass is increasing.

The last column in Table 5.10 and Figure 5.8 shows all the different sustained levels of lionfish biomass together. When a designated threshold is less than 1.7 million grams, the final sustained biomass with a derby will always be approximately 1.66 million grams. When $x^* = 1,700,000$ g to $1,800,000$ g (beyond 1.66 million grams), the sustained lionfish biomass will stay at the designated threshold of biomass. When $x^* = 1,900,000$, the lionfish derby will be held every other year and the sustained biomass in a year with a derby will remain at approximately 1.66 million grams. Note that all final sustained lionfish biomass

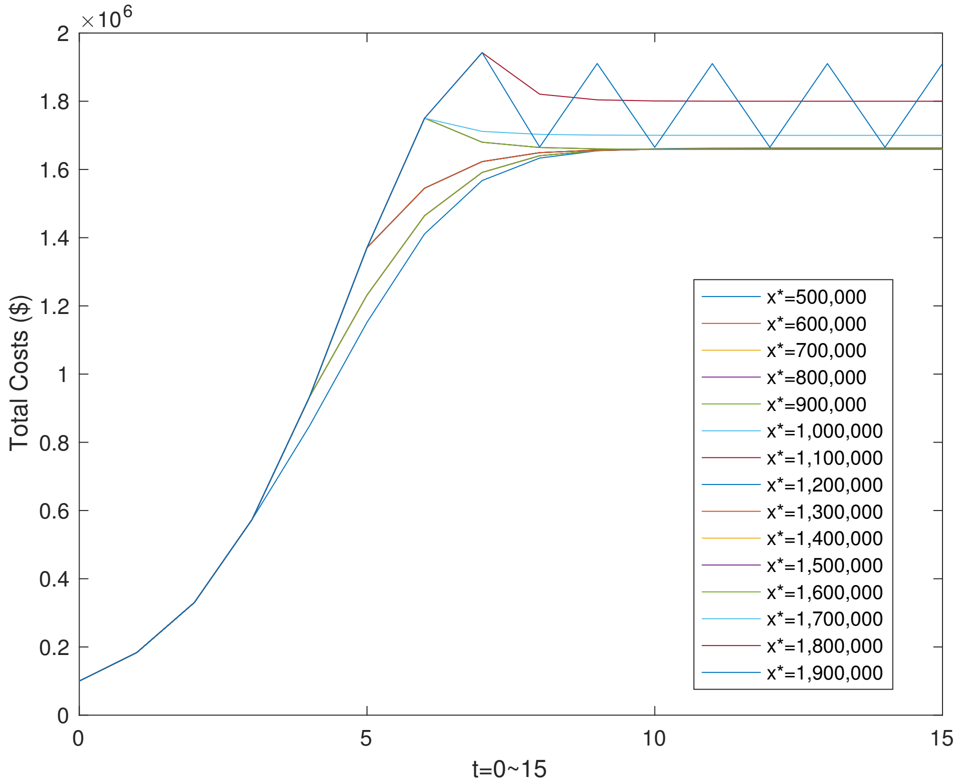


Figure 5.8: Sustained Lionfish Biomass Level with Lionfish Derby (t=0-15)

levels will be greater than x^* when $x^* \leq 1,600,000$ g.

Discussion

When derby managers review Table 5.10, they must choose the *best* x^* based on their considerations, then they can use a solver to find a more accurate p^* that minimizes the sum of lionfish damage and prize money. How can we explain the above interesting features of Table 5.10? Some math functions can help us understand them.

Table 5.11 and Table 5.12 help to illustrate how lionfish biomass, harvest rate, award prizes and costs change over time. Note that time period t is from 0 to 99, a total of 100 periods.

In Table 5.11, it shows the evolution of the path of lionfish biomass $x^* \in [10, 11, 12, 13]\times10^5$. It is interesting to observe that the threshold award prize and minimum total costs are the same as each other. In order to explain this, we need to review our dynamic optimization system: Since

$$G(x_t) = r(1 - \frac{x_t}{K})x_t$$
$$k(x_t) = \frac{d}{2}x_t^2$$
$$h(p_t, x_t) = mp_t^{\beta}x_t$$

Then the objective function can be rewritten as:

$$\underset{[x^*,p^*]}{\text{Min}}\ C = \sum_{t=0}^{T}\rho^t[k_t + p_t] = \sum_{t=0}^{T}\rho^t[\frac{d}{2}x_t^2 + p_t] \tag{5.5}$$

and constrained conditions then are:

$$x_{t+1} - x_t = G_t - h_t \tag{5.6}$$
$$= r(1 - \frac{x_t}{K})x_t - mp_t^{\beta}x_t,\ given\ x_0 > 0 \tag{5.7}$$
$$x_{t+1} = (1 + r - \frac{r}{K}x_t - mp_t^{\beta})x_t \tag{5.8}$$

$$If\ x_t \geqslant x^*,\ p_t = p^* \tag{5.9}$$

$$If\ x_t < x^*,\ p_t = 0 \tag{5.10}$$

From Equation (5.8), two key variables, lionfish biomass in year t (x_t) and award prize in year t (p_t), play an important role in determining the next period's lionfish biomass (x_{t+1}). We can iterate beginning steps to see how x_t and p_t are determined. The initial lionfish biomass in time $t = 0$ is $x_0 = 100,000$, then based on Equation (5.5), Equation (5.8), Equation (5.9) and Equation (5.10),

$$\begin{aligned} x_1 &= (1 + r - \frac{r}{K}x_0 - mp_0^{\beta})x_0 \\ C_0 &= \rho^0[\frac{d}{2}x_0^2 + p_0] \end{aligned}$$

that both x_1 and C_0 is a function of x_0 and p_0. In order to simplify the equation, I just use

$$\begin{aligned} x_1 &= f_0(x_0,\ p_0) \\ C_0 &= g_0(x_0,\ p_0) \end{aligned}$$

where f_0 and g_0 are all polynomial functions. Then

$$\begin{aligned} x_2 &= (1 + r - \frac{r}{K}x_1 - mp_1^{\beta})x_1 = f_1(x_1,\ p_1) \\ C_1 &= \rho^1[\frac{d}{2}x_1^2 + p_1] = g_1(x_1,\ p_1) \end{aligned}$$

replacing x_1 in the functional form of x_0 and p_0, we get

$$\begin{aligned} x_2 &= f_1(x_1,\ p_1) = f_1(f_0(x_0,\ p_0),\ p_1) = F_1(x_0,\ p_0,\ p_1) \\ C_1 &= g_1(x_1,\ p_1) = g_1(f_0(x_0,\ p_0),\ p_1) = G_1(x_0,\ p_0,\ p_1) \end{aligned}$$

where F_1 and G_1 are new polynomial functional forms. Similarly, different period values for lionfish biomass x_t and cost C_t can be expressed in a function of x_0 and different award prize p_t

$$x_3 = F_2(x_0,\ p_0,\ p_1,\ p_2),\ \ C_2 = G_2(x_0,\ p_0,\ p_1,\ p_2)$$

$$x_4 = F_3(x_0,\ p_0,\ p_1,\ p_2,\ p_3),\ \ C_3 = G_3(x_0,\ p_0,\ p_1,\ p_2,\ p_3)$$

$$\ldots\ldots \qquad\qquad\qquad\qquad \ldots\ldots$$

$$x_{99} = F_{98}(x_0,\ p_0,\ p_1, \ldots\ldots,\ p_{98}),\ \ C_{98} = G_{98}(x_0,\ p_0,\ p_1, \ldots\ldots,\ p_{98})$$

$$\textit{and}\ C_{99} = G_{99}(x_0,\ p_0,\ p_1, \ldots\ldots,\ p_{99})$$

In the end, the final total costs can be written as

$$C = \sum_{t=0}^{T} C_t = C_1 + \ldots\ldots + C_{99} = G(x_0,\ p_0,\ p_1,\ \ldots\ldots,\ p_{99})$$

where G is the final polynomial function.

Invasive-species managers are goal-oriented and they are trying to find the minimum values for total costs and threshold award prize p^* that will drive what they want. We then turn back to Table 5.11, subtable (a) (b) (c) (d) are exactly same to each other except the threshold lionfish biomass x^* is different. When $x^* = 1,000,000$, the iterative equation (5.8) can be used to calculate each period's lionfish biomass x_t. Then, comparing it to designated lionfish biomass, we can decide whether a derby should be held in time t based on constrained conditions (5.9) and (5.10). Table 5.11(a) shows that $p_t = 0$ when time t is from 0 to 4, which means a derby is not held in those times. In period $t = 5$, the lionfish biomass $x_5 = 1,370,813,25$: this is the first time it is greater than the designated x^* level and the first a derby is held with award prize p^*.

Then the total costs for lionfish threshold biomass $x^* = 1,000,000$ is

$$C = G(x_0,\ p_0,\ p_1,\ .....,\ p_{99}) \tag{5.11}$$

$$= G(x_0,\ p_5,\ p_6,\ .....,\ p_{99}),\ p_t = 0\ with\ t \in [0,\ 4] \tag{5.12}$$

Invasive-species managers use the table method and Excel Solver to locate the optimal threshold award prize $p^* = \ \$7,141.35$ when $x^* = 1,000,000$ and Equation (5.12) is minimized $C = \$2,436,762.00$. After several years of holding a lionfish derby with $p^* = \ \$7,141.35$, the lionfish biomass and award prize approach a steady state that

$$x_{t+1} = x_t > x^*,\ t >> 0$$
$$h_{t+1} = h_t$$

Based on Equation (5.9): If $x_t \geqslant x^*, p_t = p^*$, the award prize for each period is always the same when time t is much greater than 0:

$$p_{t+1} = p_t = p^*,\ t >> 0$$

In Table 5.11 (a) (b) (c) (d), lionfish biomass in time $t = 4$ is $x_4 = 932,800.21$ and in time $t = 5$ is $x_5 = 1,370,813.25$. Different lionfish biomass thresholds are all in this range of $x_4 < x^* \in [10,\ 11,\ 12,\ 13] \times 10^5 < x_5$ which means that the first derby-hold time is the same for those biomass thresholds. Thus, for

$x^* \in [11,\ 12,\ 13]{\times}10^5$, the total cost function is also

$$C = G(x_0,\ p_5,\ p_6,\ .....,\ p_{99}),\ p_t = 0\ with\ t \in [0,\ 4]$$

The table method tries different combinations and finds that $p^* =$ \$7,141.35 and $C =$ \$2,436,762.00 is also the optimal choice for those x^*. After several years of derbies, the lionfish biomass and harvest rate approach a steady state,

$$x_{t+1} = x_t > x^*,\ t >> 0$$

$$h_{t+1} = h_t$$

$$p_{t+1} = p_t = p^*,\ t >> 0$$

A similar process also applies to $x^* \in [6,\ 7,\ 8,\ 9]{\times}10^5$ where $p^* =$ \$7,050.54 and $C_{min} =$ \$2,429,717.49, and $x^* \in [14,\ 15,\ 16,\ 17]{\times}10^5$ where $p^* =$ \$7,199.62 and $C_{min} =$ \$2,446,832.00

When $x^* \in [6,\ 10,\ 14]{\times}10^5$, Table 5.12 (a)(b)(c) shows that p^* and C_{min} are increasing when x^* is increasing. The reason is that the first derby-hold time is different and then the total cost function is different and it results in a different threshold award prize p^* when using the table method.

$$C = G(x_0,\ p_4,\ p_5,\ .....,\ p_{99}),\ p_t = 0\ with\ t \in [0,\ 3],\ x^* = 600{,}000$$

$$C = G(x_0,\ p_5,\ p_6,\ .....,\ p_{99}),\ p_t = 0\ with\ t \in [0,\ 4],\ x^* = 1{,}000{,}000$$

$$C = G(x_0,\ p_6,\ p_7,\ .....,\ p_{99}),\ p_t = 0\ with\ t \in [0,\ 5],\ x^* = 1{,}400{,}000$$

However, all those lionfish biomass thresholds are lower than the sustained lionfish biomass after holding derbies for several years. Thus, for each threshold biomass x^*, lionfish biomass and harvest rate approach the steady state,

$$x_{t+1} = x_t > x^*, \ t >> 0$$
$$h_{t+1} = h_t$$
$$p_{t+1} = p_t = p^*, \ t >> 0$$

This raises another question: when reviewing Table 5.10, lionfish threshold biomass $x^* = 1,600,000$ and $x^* = 1,700,000$ start the first derby in the 7th year (t=6), so why do they have different values for threshold award prize p^* and total costs? The reason is that sustained lionfish biomasses are different after several years are different. If the award prize is unchanged so that $p^* = \$7,199.62$ when $x^* = 1,700,000$, then it must happen that at some lionfish biomass levels $x_t < x^*$ and constrained condition (5.10) a derby will not be held at that time. The total cost function is different: $x^* = 1,700,000$ and $p^* = \$7,199.62$ will result in a periodical derby while $x^* = 1,600,000$ and $p^* = \$7,199.62$ will approach a steady state.

$$C = G(x_0, \ p_6, \ p_7, \ ....., \ p_{99}), \ p_t = 0 \ with \ t \in [0, \ 5], \ x^* = 1,600,000$$
$$C = G(x_0, \ p_6, \ ....., \ p_i, ..., \ p_{99}), \ p_t = 0 \ with \ t \in [0, \ 5], \ some \ p_i = 0, \ x^* = 1,700,000$$

Thus, when $x^* = 1,700,000$, invasive-species managers use the table method and Excel Solver to relocate optimal threshold award prizes and find out whether they exist in a local steady state for $x^* = 1,700,000$. The steady state comes to $x^* = 1,700,000$ and $p^* = \$4,866.81$,

$$
\begin{aligned}
&x_{t+1} = x_t = x^*, \ t >> 0 \\
&h_{t+1} = h_t \\
&p_{t+1} = p_t = p^*, \ t >> 0
\end{aligned}
$$

Note that the sustained lionfish biomass level equals the threshold biomass level and is greater than all previous levels. A similar situation applies to $x^* = 1,800,000$.

The last row in Table 5.10 and Table 5.12 (f) shows the threshold combination and evolution path for $x^* = 1,900,000$. The derby is held every other year and it does not have a steady state. The total costs function can be rewritten as

$$C = G(x_0, \ p_7, \ p_9, \ ....., \ p_{99}), \ p_t = 0 \ with \ t \in [0, \ 6], \ p_t = 0 \ when \ t \ is \ even, \ x^* = 1,900,000$$

After several years of holding the derby,

$$
\begin{aligned}
&x_{t+1} \neq x_t, \ x_{t+1} = x_{t-1} \ t >> 0 \\
&h_{t+1} \neq h_t, \ h_{t+1} = h_{t-1} \\
&p_{t+1} \neq p_t, \ p_{t+1} = p_{t-1} \ t >> 0
\end{aligned}
$$

We then come back to Table 5.10. How can invasive-species managers make decisions from this table? Combining this table with our previous analysis, we can review the table in three parts. When designated threshold lionfish biomass

x^* is less than the sustained lionfish biomass, the minimum total costs C_{min} and threshold award prize p^* are generally increasing and the sustained lioinfish biomass is decreasing when x^* is increasing. Note that for some threshold biomass x^*, the p^* and C_{min} don't change because they start the first derby at the same time and the total cost function is the same. In the steady state,

$$x_{t+1} = x_t > x^*, \; t >> 0$$
$$h_{t+1} = h_t$$
$$p_{t+1} = p_t = p^*, \; t >> 0$$

When the designated threshold of lionfish biomass x^* is greater than the previously calculated threshold for sustained biomass, then in each period the lioinfish biomass should always be at the x^* level, with total costs increasing. The new sustained lionfish biomass level remains at x^* and threshold award prize decreases in our simulations. In the steady state

$$x_{t+1} = x_t = x^*, \; t >> 0$$
$$h_{t+1} = h_t$$
$$p_{t+1} = p_t = p^*, \; t >> 0$$

When the designated threshold of lionfish biomass x^* reaches a very high value such that a periodical derby happens, this situation does not have a steady state. The threshold award prize and total minimum costs are highest in our simulation and the value for sustained biomass in a year with a derby approximately the same as the value for sustained biomass when x^* value is small.

$$x_{t+1} \neq x_t, \; x_{t+1} = x_{t-1} \; t >> 0$$

$$h_{t+1} \neq h_t, \; h_{t+1} = h_{t-1}$$

$$p_{t+1} \neq p_t, \; p_{t+1} = p_{t-1} \; t >> 0$$

Table 5.11: Evolution Excerpts for Different Lionfish Threshold Biomass $x^* \in [10,\ 11,\ 12,\ 13] \times 10^5$

(a) x^*=1,000,000, p^*= \$7,141.35, C_{min}= \$2,436,762.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	7,141.35	205,199.33	1,370,813.25	40,507.84
6	7,141.35	231,290.53	1,545,112.83	48,739.71
7	7,141.35	242,961.14	1,623,077.19	52,084.70
8	7,141.35	246,886.02	1,649,296.96	52,528.03
9	7,141.35	248,026.06	1,656,912.86	51,919.46
10	7,141.35	248,340.23	1,659,011.62	51,015.61
11	7,141.35	248,425.46	1,659,581.01	50,045.70
12	7,141.35	248,448.49	1,659,734.82	49,072.46
13	7,141.35	248,454.70	1,659,776.32	48,112.39
14	7,141.35	248,456.37	1,659,787.51	47,169.57
15	7,141.35	248,456.82	1,659,790.53	46,244.83
…..	…..	…..	…..	…..
99	7,141.35	248,456.99	1,659,791.65	8,762.93

(b) x^*=1,100,000, p^*= \$7,141.35, C_{min}= \$2,436,762.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	7,141.35	205,199.33	1,370,813.25	40,507.84
6	7,141.35	231,290.53	1,545,112.83	48,739.71
7	7,141.35	242,961.14	1,623,077.19	52,084.70
8	7,141.35	246,886.02	1,649,296.96	52,528.03
9	7,141.35	248,026.06	1,656,912.86	51,919.46
10	7,141.35	248,340.23	1,659,011.62	51,015.61
11	7,141.35	248,425.46	1,659,581.01	50,045.70
12	7,141.35	248,448.49	1,659,734.82	49,072.46
13	7,141.35	248,454.70	1,659,776.32	48,112.39
14	7,141.35	248,456.37	1,659,787.51	47,169.57
15	7,141.35	248,456.82	1,659,790.53	46,244.83
…..	…..	…..	…..	…..
99	7,141.35	248,456.99	1,659,791.65	8,762.93

(c) x^{*}=1,200,000, p^{*}= \$7,141.35, C_{min}= \$2,436,762.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	7,141.35	205,199.33	1,370,813.25	40,507.84
6	7,141.35	231,290.53	1,545,112.83	48,739.71
7	7,141.35	242,961.14	1,623,077.19	52,084.70
8	7,141.35	246,886.02	1,649,296.96	52,528.03
9	7,141.35	248,026.06	1,656,912.86	51,919.46
10	7,141.35	248,340.23	1,659,011.62	51,015.61
11	7,141.35	248,425.46	1,659,581.01	50,045.70
12	7,141.35	248,448.49	1,659,734.82	49,072.46
13	7,141.35	248,454.70	1,659,776.32	48,112.39
14	7,141.35	248,456.37	1,659,787.51	47,169.57
15	7,141.35	248,456.82	1,659,790.53	46,244.83
…..	…..	…..	…..	…..
99	7,141.35	248,456.99	1,659,791.65	8,762.93

(d) x^{*}=1,300,000, p^{*}= \$7,141.35, C_{min}= \$2,436,762.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	7,141.35	205,199.33	1,370,813.25	40,507.84
6	7,141.35	231,290.53	1,545,112.83	48,739.71
7	7,141.35	242,961.14	1,623,077.19	52,084.70
8	7,141.35	246,886.02	1,649,296.96	52,528.03
9	7,141.35	248,026.06	1,656,912.86	51,919.46
10	7,141.35	248,340.23	1,659,011.62	51,015.61
11	7,141.35	248,425.46	1,659,581.01	50,045.70
12	7,141.35	248,448.49	1,659,734.82	49,072.46
13	7,141.35	248,454.70	1,659,776.32	48,112.39
14	7,141.35	248,456.37	1,659,787.51	47,169.57
15	7,141.35	248,456.82	1,659,790.53	46,244.83
…..	…..	…..	…..	…..
99	7,141.35	248,456.99	1,659,791.65	8,762.93

Table 5.12: Evolution Excerpts for Different Lionfish Threshold Biomass $x^* \in [6,\ 10,\ 14,\ 17,\ 18,\ 19]\times 10^5$

(a) x^*=600,000, p^*= \$7,050.54, C_{min}= \$2,429,717.49

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	7,050.54	139,047.49	932,800.21	22,590.67
5	7,050.54	183,612.67	1,231,765.76	33,870.23
6	7,050.54	218,307.84	1,464,518.33	44,351.34
7	7,050.54	237,201.80	1,591,268.49	50,225.44
8	7,050.54	244,502.22	1,640,243.38	51,942.15
9	7,050.54	246,758.57	1,655,380.06	51,758.50
10	7,050.54	247,392.28	1,659,631.37	50,974.85
11	7,050.54	247,564.86	1,660,789.12	50,037.18
12	7,050.54	247,611.45	1,661,101.66	49,072.43
13	7,050.54	247,624.00	1,661,185.83	48,114.55
14	7,050.54	247,627.38	1,661,208.48	47,172.27
15	7,050.54	247,628.28	1,661,214.58	46,247.63
…..	…..	…..	…..	…..
99	7,050.54	247,628.62	1,661,216.82	8,763.47

(b) x^*=1,000,000, p^*= \$7,141.35, C_{min}= \$2,436,762.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	7,141.35	205,199.33	1,370,813.25	40,507.84
6	7,141.35	231,290.53	1,545,112.83	48,739.71
7	7,141.35	242,961.14	1,623,077.19	52,084.70
8	7,141.35	246,886.02	1,649,296.96	52,528.03
9	7,141.35	248,026.06	1,656,912.86	51,919.46
10	7,141.35	248,340.23	1,659,011.62	51,015.61
11	7,141.35	248,425.46	1,659,581.01	50,045.70
12	7,141.35	248,448.49	1,659,734.82	49,072.46
13	7,141.35	248,454.70	1,659,776.32	48,112.39
14	7,141.35	248,456.37	1,659,787.51	47,169.57
15	7,141.35	248,456.82	1,659,790.53	46,244.83
…..	…..	…..	…..	…..
99	7,141.35	248,456.99	1,659,791.65	8,762.93

(c) x^{*}=1,400,000, p^{*}= \$7,199.62, C_{min}= \$2,446,832.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100000.00	200.00
1	0	0	183600.00	660.96
2	0	0	330336.06	2097.69
3	0	0	573018.15	6188.23
4	0	0	932800.21	16077.06
5	0	0	1370813.25	34039.70
6	7199.62	262706.45	1750312.16	60800.71
7	7199.62	252138.15	1679899.64	55403.22
8	7199.62	249806.62	1664365.54	53430.10
9	7199.62	249204.08	1660351.03	52159.08
10	7199.62	249043.18	1659279.02	51077.97
11	7199.62	248999.85	1658990.36	50061.03
12	7199.62	248988.16	1658912.45	49075.37
13	7199.62	248985.00	1658891.42	48112.03
14	7199.62	248984.15	1658885.74	47168.37
15	7199.62	248983.92	1658884.20	46243.42
…..	…..	…..	…..	…..
99	7,199.62	248,983.84	1,658,883.64	8,762.65

(d) x^{*}=1,700,000, p^{*}= \$4,866.81, C_{min}= \$2,460,062.42

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	0	0	1,370,813.25	34,039.70
6	4,866.81	231,041.09	1,750,312.16	58,729.24
7	4,866.81	225,926.47	1,711,565.00	55,242.18
8	4,866.81	224,776.83	1,702,855.64	53,651.39
9	4,866.81	224,494.42	1,700,716.15	52,477.54
10	4,866.81	224,423.69	1,700,180.36	51,418.67
11	4,866.81	224,405.90	1,700,045.55	50,403.09
12	4,866.81	224,401.42	1,700,011.59	49,412.97
13	4,866.81	224,400.29	1,700,003.03	48,443.64
14	4,866.81	224,400.00	1,700,000.88	47,493.65
15	4,866.81	224,399.93	1,700,000.33	46,562.38
…..	…..	…..	…..	…..
99	4,866.81	224,399.91	1,700,000.15	8,823.09

(e) x^*=1,800,000, p^*= \$1,413.78, C_{min}= \$2,598,228.97

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	0	0	1,370,813.25	34,039.70
6	0	0	1,750,312.16	54,407.65
7	1,413.78	170,949.24	1,942,606.09	66,935.76
8	1,413.78	160,222.75	1,820,714.10	57,793.05
9	1,413.78	158,762.46	1,804,119.83	55,653.21
10	1,413.78	158,474.67	1,800,849.54	54,368.55
11	1,413.78	158,415.44	1,800,176.47	53,263.51
12	1,413.78	158,403.15	1,800,036.78	52,211.20
13	1,413.78	158,400.59	1,800,007.74	51,185.83
14	1,413.78	158,400.06	1,800,001.70	50,181.86
15	1,413.78	158,399.95	1,800,000.44	49,197.83
…..	…..	…..	…..	…..
99	1,413.78	158,399.92	1,800,000.11	9,322.48

(f) x^*=1,900,000, p^*= \$10,130.88, C_{min}= \$2,711,309.00

Time (t)	Award Prize (p_t)	Harvest Rate (h_t)	Biomass (x_t)	Costs ($\rho^t C_t$)
0	0	0	100,000.00	200.00
1	0	0	183,600.00	660.96
2	0	0	330,336.06	2,097.69
3	0	0	573,018.15	6,188.23
4	0	0	932,800.21	16,077.06
5	0	0	1,370,813.25	34,039.70
6	0	0	1,750,312.16	54,407.65
7	10,130.90	326,133.08	1,942,606.09	74,524.53
8	0	0	1,665,530.26	47,351.49
9	10,130.90	320,766.61	1,910,640.83	69,569.39
10	0	0	1,664,996.86	45,483.63
11	10,130.90	320,729.49	1,910,419.70	66,854.34
12	0	0	1,664,990.04	43,717.09
13	10,130.90	320,729.01	1,910,416.87	64,258.13
14	0	0	1,664,989.95	42,019.49
15	10,130.90	320,729.01	1,910,416.83	61,762.91
…..	…..	…..	…..	…..
99	10,130.90	320,729.01	1,910,416.83	11,703.43

5.3.4 Sensitivity Analysis Results

Influence of the Environmental Carrying Capacity

Table 5.13: Sensitivity Analysis of Carrying Capacity (K)

Carrying Capacity Change K	Threshold Award Prize p^*	Total Costs	Sustained Lionfish Biomass	Team Number N	Harvest Rate h
1,200,000	$1,755.41	$983,748	1,032,658.49	12	97,559.63
1,400,000	$2,696.76	$1,299,574	1,204,768.23	13	131,031.95
1,600,000	$3,896.67	$1,648,988	1,376,877.98	15	168,966.49
1,800,000	$5,373.27	$2,028,981	1,521,088.92	17	207,410.44
2,000,000	$7,141.35	$2,436,762	1,659,791.65	18	248,456.94
2,200,000	$9,212.70	$2,869,737	1,793,166.70	20	291,807.99
2,400,000	$11,596.36	$3,325,489	1,921,387.94	22	337,186.46
2,600,000	$14,298.92	$3,801,771	2,044,623.18	23	384,335.37
2,800,000	$17,065.86	$4,282,165	2,166,172.61	24	431,507.85

[a] The Reference Case is $K = 2,000,000$.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

Table 5.13 shows how corresponding threshold award prize, total costs, sustained lionfish biomass, team number and harvest rate change when carrying capacity changes. Table 5.14 presents threshold award prize and total cost elasticity results of environmental carrying capacity. All of the results are based on the assumption that an invasive-species manager will keep the threshold lionfish biomass at $x^* = 1,000,000$ g.

Table 5.14: Sensitivity Analysis of Carrying Capacity (K) (cont'd)

Carrying Capacity Change K	Percentage Change of K	Elasticity of p^*	Elasticity of Total Costs
1,200,000	-40%	+1.89	+1.49
1,400,000	-30%	+2.07	+1.56
1,600,000	-20%	+2.27	+1.62
1,800,000	-10%	+2.48	+1.67
2,000,000	0%	-	-
2,200,000	10%	+2.90	+1.78
2,400,000	20%	+3.12	+1.82
2,600,000	30%	+3.34	+1.87
2,800,000	40%	+3.47	+1.89

[a] The Reference Case is $K = 2,000,000$.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

In Table 5.13, the first column shows different levels of carrying capacity. Column two presents the corresponding threshold prize. Column three presents the total costs. Column four is the final sustained lionfish biomass level with different carrying capacities and prizes. Column five is the calculated team numbers that participate in the derby. Column six is the sustained harvest rate when lionfish biomass is sustained.

In Table 5.14, the first column is still different carrying capacity levels and column two shows their percentage change compared with the reference case of $K = 2,000,000$ g. The range of carrying capacity lies between -40% and

+40% of the referred carrying capacity. Column three is the threshold award prize elasticity and column four is the elasticity of total costs.

Changes in the environmental carrying capacities have different effects on threshold prizes, total costs, and the final sustained lionfish biomass level. As we see in Table 5.13 and Table 5.14, the prize decreases when carrying capacity decreases and it increases when carrying capacity increases. When carrying capacity increases from 1.2×10^6 to 2.8×10^6, the threshold award prize is elastic since its elasticity value is always greater than 1. The elasticity of threshold award prize is increasing as carrying capacity is increasing, which means that threshold award prize becomes more and more sensitive: it is 1.89 when carrying capacity is $1,200,000$. This means that with a threshold biomass x^* of 1,000,000 g, a 1% increase in carrying capacity will increase the corresponding designated prize by 1.89%. As the carrying capacity increases 40%, the prize elasticity is then 3.47, which means a 1% increase in carrying capacity will lead to a 3.47% increase in prize money.

Total cost increases when carrying capacity increases. The total cost is elastic since its elasticity value is also greater than one as carrying capacity increases. The elasticity of total cost increases when carrying capacity increases and suggests that total costs become more sensitive to carrying capacity when designated lionfish biomass is kept at approximately 1,000,000 g : 1.49 when $K = 1,200,000$ means that a 1% increase in carrying capacity will lead to a 1.49% increase in total cost. Similarly, 1.89 when $K = 2,800,000$ means that a 1% increase in carrying capacity and that total cost will increase 1.89%. Compared with prize elasticity, total cost elasticity is lower. This suggests that total cost is not as sensitive to carrying capacity as award prize is.

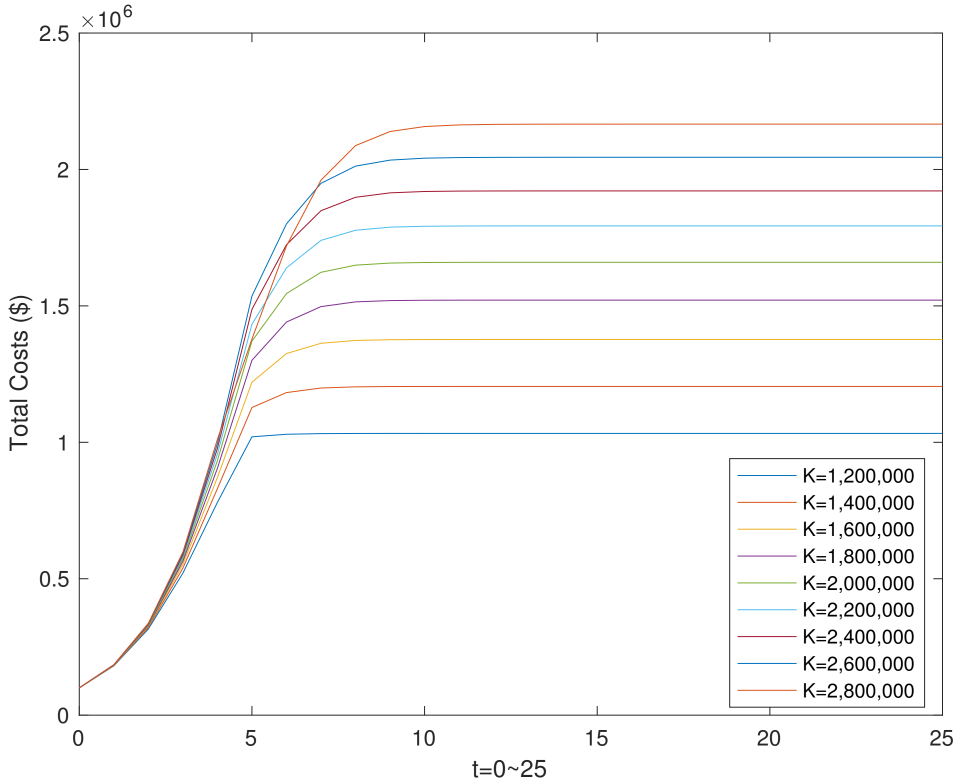


Figure 5.9: Sensitivity Analysis of Carrying Capacity K (t=0-25)

We then turn back to Table 5.13, where the final sustained lionfish biomass levels are all greater than the designated threshold lionfish biomass $x^* = 1,000,000$ g and the levels increase when carrying capacity increases. Based on our team-number-prize equation (3.9) $N_t = p_t^\beta$ and $\beta = 0.328$, we can calculate the expected number of participating teams number for different values of sustained lionfish biomass. It shows that more teams will come to join the derby when carrying capacity increases. For the harvest rate, we can calculate the sustained harvest rate from Equation (3.10) where coefficient $m = 0.00815$. It shows that the harvest rate is also increasing when carrying capacity K is increasing.

Influence of the Discount Rate δ

Table 5.15: Sensitivity Analysis of Discount Rate (δ)

Discount Rate δ	Threshold Award Prize p^*	Total Costs	Sustained Lionfish Biomass	Team Number N	Harvest Rate h
0.01	$7,248.77	$3,656,370.76	1,658,121.57	18	249,425.44
0.02	$7,141.35	$2,436,762.00	1,659,791.65	18	248,456.94
0.04	$6,893.65	$1,298,809.87	1,663,708.09	18	246,176.25
0.06	$6,634.96	$819,853.25	1,667,900.69	18	243,719.79
0.08	$6,384.48	$573,419.16	1,672,066.27	18	241,263.82
0.1	$6,147.26	$427,426.33	1,676,113.71	17	238,862.89

[a] The Reference Case is $\delta = 0.02$.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

To determine the influence of the discount rate on threshold prize money, total cost, and sustained lionfish biomass level, simulations are conducted with various discount rates ranging from 1% to 10%.

In Table 5.16, the sign of award prize elasticity presents a reverse relationship between award prize and the discount rate: when the discount rate decreases, the award prize increases; when the discount rate increases, the prize decreases. However, since all absolute value of elasticities remain at approximately 0.035, which means a 1% increase or decrease in the discount rate, the corresponding threshold prize will decrease or increase by 0.035%. The threshold award prize is inelastic to discount rate and it is not sensitive to change of discount rate.

The minus sign of total costs elasticity shows that total cost decreases when

Table 5.16: Sensitivity Analysis of Discount Rate (δ) (cont'd)

Discount Rate δ	Percentage Change of δ	Elasticity of p^*	Elasticity of Total Costs
0.01	-50%	-0.0301	-1.001
0.02	0%	-	-
0.04	100%	-0.0347	-0.467
0.06	200%	-0.0355	-0.332
0.08	300%	-0.0353	-0.255
0.1	400%	-0.0348	-0.206

[a] The Reference Case is $\delta = 0.02$.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

the discount rate increases. To calculate the overall total cost, each period of environmental cost needs to be discounted to its present value. The higher the discount rate, the lower the present value will be. The absolute value of elasticity decreases when the discount rate increases but it is lower than 1 except when the discount rate is 0.01 and the elasticity is around 1. Thus it is inelastic when discount rate is greater than 0.01. When the discount rate grows higher, total cost elasticity is decreasing which means that it becomes less sensitive to it.

Now turning back to Table 5.15, the discount rate plays an important role in calculating total cost but not in the lionfish population dynamics system; thus the sustained lionfish biomass grows slightly between 1.66 to 1.67 million grams. Figure 5.10 shows a different trajectory of lionfish biomass with derbies. Similarly, based on Equation (3.9) and (3.10), team numbers are keeping around

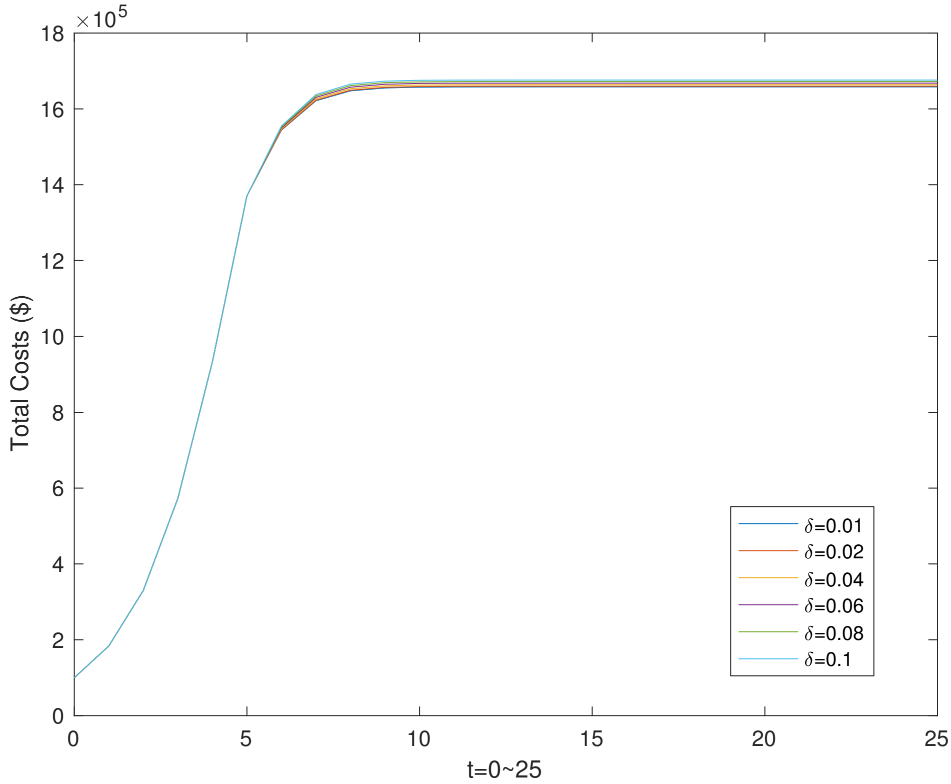


Figure 5.10: Sensitivity Analysis of Discount Rate (t=0-25)

18 and harvest rates are slightly decreasing from $2.5 \times 10^5 g to 2.4 \times 10^5 g$.

Influence of the Environmental Damage Coefficient d

Since the environmental damage coefficient is calculated from several assumptions, it is important to consider its impact on prize money and total cost. It can be expected that an increase in the damage coefficient will have a positive influence on total cost. Simulations are conducted with the damage coefficient ranging from 1×10^{-8} to 1×10^{-7}.

The results show that prize money increases when damage coefficient in-

Table 5.17: Sensitivity Analysis of Damage Coefficient (d)

Damage Coefficient d	Threshold Award Prize p^*	Total Costs	Sustained Lionfish Biomass	Team Number N	Harvest Rate h
0.00000001	$1,041.40	$684,677.68	1,819,081.63	10	144,806.44
0.00000002	$2,758.64	$1,303,984.50	1,750,969.25	13	191,859.88
0.00000004	$7,141.35	$2,436,762.00	1,659,791.38	18	248,456.90
0.00000006	$12,281.80	$3,472,730.45	1,593,572.68	22	284,975.44
0.00000008	$17,902.52	$4,437,273.87	1,540,102.75	25	311,647.17
0.0000001	$23,855.83	$5,344,614.80	1,494,692.25	27	332,323.02

[a] The Reference Case is d = 0.00000004.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

Table 5.18: Sensitivity Analysis of Damage Coefficient (d) (cont'd)

Damage Coefficient d	Percentage Change of δ	Elasticity of p^*	Elasticity of Total Costs
0.00000001	-75%	+1.14	+0.96
0.00000002	-50%	+1.23	+0.93
0.00000004	0%	-	-
0.00000006	50%	+1.44	+0.85
0.00000008	100%	+1.51	+0.82
0.0000001	150%	+1.56	+0.80

[a] The Reference Case is d = 0.00000004.

[b] Threshold Lionfish Biomass $x^* = 1,000,000\ g$.

creases. All absolute value of elasticities are greater than 1. This means threshold award prize is elastic that a 1% increase in the damage coefficient will result in more than a 1% increase in the prize. The increasing award prize elasticity indicates that prizes become more and more sensitive to damage coefficient when d increases.

The total costs increases with an increasing damage coefficient. The first feature is that total cost elasticities are all positive but less than 1 which means that total cost elasticity is inelastic that a 1% increase in damage coefficient will lead to less than a 1% increase in total cost. The second feature is that elasticities decrease as total cost becomes less sensitive to increasing damage coefficient. The third feature is that the elasticity of threshold award prize is always greater than total cost elasticity which means that award prize is more sensitive to damage change than total cost.

The sustained lionfish biomass level has a reverse relationship with the damage coefficient: When the environmental damage coefficient is 1×10^{-8}, the sustained lionfish biomass level reaches its highest level; when the damage coefficient is 1×10^{-7}, the sustained lionfish biomass level reaches its lowest level. However, all sustained lionfish biomass levels are greater than invasive-species manager-designed thresholds for lionfish biomass $x^* = 1,000,000$ g. Based on Equation (3.9) and (3.10), team number and harvest rate are always increasing as damage coefficient is increasing.

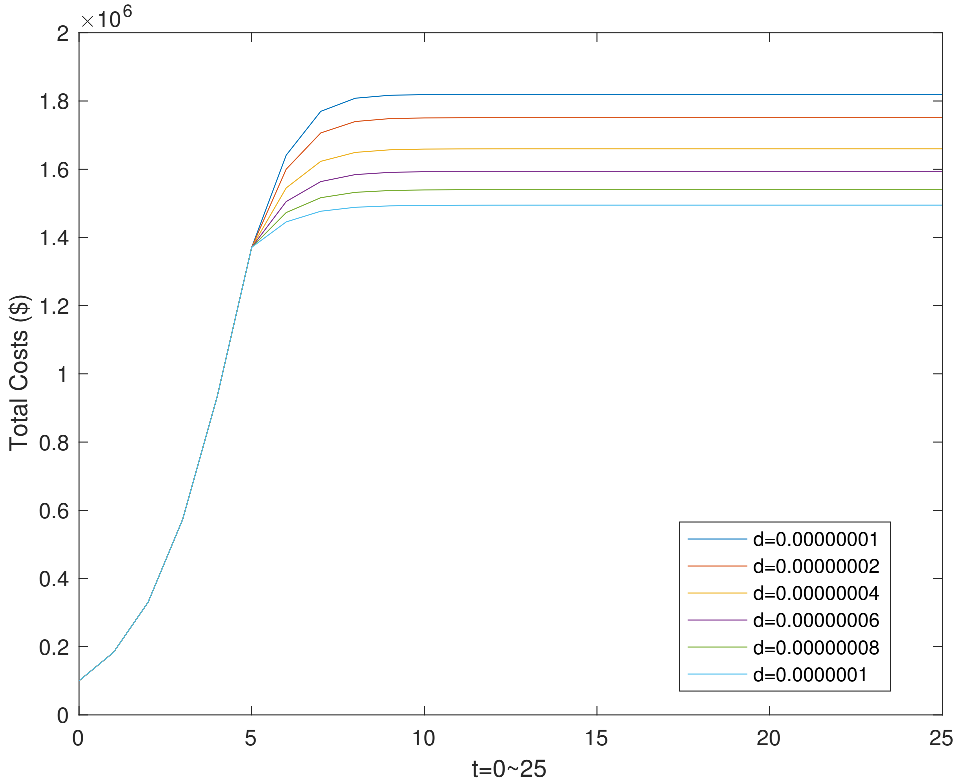


Figure 5.11: Sensitivity Analysis of Environmental Damage Coefficient d (t=0-25)

Discussion

From our simulation results, changes in carrying capacity, discount rate and damage coefficient all have different impacts on threshold award prize, total costs, sustained lionfish biomass, team number and harvest rate.

Increases in carrying capacity all have positive impacts on other variables: the award prize is increasing; more teams will participate in the derby, which means that the fishing effort is increasing; the harvest rate is increasing so that more lionfish can be removed. However, the sustained lionfish biomass also grows and minimum total costs grows higher due to higher carrying capacity.

Compared with carrying capacity, increases in the discount rate don't have much impact on those variables. Although total costs decrease as the discount rate increases, all other variables-threshold award prize, sustained lionfish biomass, team number, and harvest rate-are slightly increasing or decreasing but almost remain at a certain level. The discount rate is important in calculating the present value of total costs, but it doesn't involve much in terms of the population dynamics system.

Increases in damage coefficient help decrease the sustained lionfish biomass and threshold award prize, team number, and harvest rate are all increasing. However, total costs are increasing as well.

Simulation results help Invasive-species manager understand how some parameters affect different variables. They can make better decisions in the future when choosing or calculating those parameters.

CHAPTER 6

CONCLUSIONS

The main objective of this paper is to construct a bioeconomic model that combines lionfish population dynamics with derby harvests in order to assess derby-controlling effects on an invasive species and how to determine optimal derby prize money, total costs, and sustained lionfish biomass.

Previous research on the lionfish derby in Key Largo, Florida, has tried to evaluate derby effects. Dr. Green's prey–predation model is based on the assumption that invasive lionfish will consume native species for food; therefore, lionfish biomass can be estimated by the reduced number of native prey. Dr. Green also tried to simulate volunteers' catch-per-unit effort based on derby information. Research conducted by Cruz, Chaves, and Cote suggests that management of an invasive species can be facilitated by public participation and its success was best predicted by national wealth (GDP per capita) and the number of local dive shops.

It is difficult to find research on lionfish that incorporates an ecological model with economic factors. My model simplifies lionfish population dynamics and participants' fishing efforts (how human behavior can affect lionfish biomass). Lionfish population dynamics follows a logistic net growth function, and lionfish harvest function adopts a simple catch-per-unit effort production function that simplifies participants by considering them as members of countable teams.

There are three main questions I seek to answer are these:

(1) Does a derby-designated lionfish threshold $[x^*, \ p^*]$ have control effects

on lionfish biomass?

(2) How can invasive-species manager make decisions in choosing appropriately designated values for lionfish biomass x^* and award prize p^*?

(3) How are optimal prize money, total costs, and sustained lionfish biomass levels affected by a change in each bioeconomic parameter?

Based on the simulated results, a derby surely does have an effect on controlling local lionfish to a certain level. In a year when there is no derby held, the total cost of control is highest and reaches \$3.1 million. A derby year with a random threshold combination has a lower cost than the off-year. In order to evaluate each threshold's combination of controlling effects, we look at corresponding total costs and sustained lionfish biomass. Although total costs and sustained lionfish biomass have a slight change when the designated threshold x^* increases, still, the sustained level is always around 1.66 million grams. This is the case when the threshold lionfish biomass x^* is lower than the sustained lionfish biomass. When x^* is greater than this sustained derby level, the derby will help to reduce lionfish to this x^* level, or a periodic derby can help keep the fish at this sustained level. However, the minimum total cost is also increasing. In this way, designated thresholds help control lionfish biomass but are of limited use when lionfish biomass reaches a certain level.

Changing environmental conditions of marine ecosystems are likely to have a profound impact on the population dynamics of lionfish. Our simulations show that the extent of change in prize money and total costs are greater for the change in carrying capacity. Smaller carrying capacity generally leads to decreased prize money and total costs, while increased carrying capacity has a much more positive impact on prize money and total costs (which are more sensitive to carrying capacity changes). Although the designated threshold of lionfish biomass remains at 1,000,000 g, the sustained lionfish biomass was never controlled below this level and it increases when carrying capacity increases. Team number and harvest rate is also increasing. Turning to evaluate discount rate impacts, these do not have much influence on prize money, sustained lionfish biomass, team number, and harvest rate, but the calculated total cost is decreasing: the great increases in discount rates lead to small decreases in prizes and other variables, except total cost. Also, the final, sustained lionfish biomass is still approximately 1.66 million grams. The increasing damage coefficient surely leads to decreasing sustained lionfish biomass. The optimal award prize, total costs, team number and harvest rate all present a certain positive proportional change.

This paper also points out the importance of accurate and sufficient data.When calibrating related parameters, such as the congestion parameter in the participant prize relation function or harvest function coefficient m, information from the derbies was not sufficient to do persuasive econometric analysis. The award prize used in our simulation remains at \$3,550, except it is \$3,625 in 2013. If prize money is ranging from \$2,000 to \$20,000, it is helpful to better estimate the congestion parameter β, thus determining the response of the number of four-person teams to award prize money. Although those values are discounted to their real price taking 2010 as the base year, there is not enough variation in prize money to see a more accurate relation between team number and award prize. The environmental costs damage coefficient is based on an assumption that environmental costs from lionfish is \$0.02/ha which is a much lower estimate than its real costs. Other methods, such as the travel cost model or contingent valuation methods, also need abundant information from derby participants. Continuing to record data and monitor the effects of derbies is required for future research work.

For derby organizers, It is suggested from harvest function $h = qE_t x_t = q(aN_t)x_t = qap_t^{\beta} x_t = mp_t^{\beta} x_t$ that harvest function coefficient m and congestion parameter β help determine a more efficient derby in which derby organizers have direct control of these parameters. Other parameters, such as carrying capacity or lionfish damage coefficient are measured objectively and we have less impact on them. Besides calibrating them more accurately, derby organizers should think about how to improve m and β to help increase derby performance. The award prize discussed in our model suggests a higher award prize attracts more participants to join in the derby. However, for each team, a higher award prize will drive their interest to catch as many lionfish as they can. This is not only true for winners, it also increases harvest biomass for non-prize-winners.

It is hoped that the model constructed in this paper will be used as a reference tool by REEF for future lionfish control management—either in monitoring lionfish, recording data, analyzing derbies, or making plans. It is also hoped that other invasive species managers, related institutions and governments, can take cues in constructing other incentive programs against invasive species.

APPENDIX A

INVASIVE SPECIES IN KEY LARGO, FLORIDA

Group	Family	Scientific Name	Common Name	Native or Exotic	Fresh, Marine or Brackish
Amphibians-Frogs	Bufonidae	Rhinella marina	Cane Toad	Native	Freshwater
Amphibians-Frogs	Eleuthero-dactylidae	Eleuthero-dactylus planirostris	Greenhouse Frog	Exotic	Freshwater
Amphibians-Frogs	Hylidae	Osteopilus septentrion-alis	Cuban Treefrog	Exotic	Group
Crustaceans-Copepods	Cyclopidae	Bryocyclops muscicola	a copepod	Exotic	Freshwater
Crustaceans-Copepods	Cyclopidae	Mesocyclops ogunnus	a copepod	Exotic	Freshwater
Crustaceans-Copepods	Cyclopidae	Paracyclops bromelia-cola	a copepod	Exotic	Freshwater
Fishes	Characidae	Colossoma Piaractus sp.	unidentified pacu	Exotic	Freshwater
Fishes	Characidae	Piaractus brachypo-mus	pirapatinga	red-bellied pacu	Exotic
Fishes	Cichlidae	Cichlasoma urophthal-mus	Mayan Cichlid	Exotic	Freshwater
Fishes	Cichlidae	Hemichromis letourneuxi	African Jewelfish	Exotic	Freshwater-Brackish
Fishes	Cichlidae	Herichthys cyanogutta-tus	Rio Grande Cichlid	Native	Freshwater
Fishes	Cichlidae	Oreochromis sp.	Tilapia species	Exotic	Freshwater
Fishes	Cichlidae	Thorichthys meeki	Firemouth Cichlid	Exotic	Freshwater

Table A.1: Invasive Species in Key Largo, Florida

Fishes	Cichlidae	Sarotherodon melanotheron	Blackchin Tilapia	Exotic	Freshwater
Fishes	Clariidae	Clarias batrachus	Walking Catfish	Exotic	Freshwater
Fishes	Grammatidae	Gramma loreto	Fairy Basslet	Exotic	Marine
Fishes	Osteoglossidae	Osteoglossum bicirrhosum	Silver Arowana	Exotic	Freshwater
Fishes	Poeciliidae	Belonesox belizanus	Pike Killifish	Exotic	Freshwater
Fishes	Scorpaenidae	Pterois volitans/miles	lionfish	Exotic	Marine
Mollusks-Gastropods	Muricidae	Rapana venosa	veined rapa whelk	Exotic	Marine
Plants	Amaranthaceae	Alternanthera philoxeroides	alligator-weed	Exotic	Freshwater
Plants	Pteridaceae	Ceratopteris thalictroides	watersprite	Native	Freshwater
Reptiles-Turtles	Chelydridae	Chelydra serpentina	Snapping Turtle	Native	Freshwater
Reptiles-Turtles	Emydidae	Deirochelys reticularia chrysea	Florida Chicken Turtle	Native	Freshwater
Reptiles-Turtles	Emydidae	Pseudemys nelsoni	Florida Red-bellied Cooter	Native	Freshwater
Reptiles-Turtles	Emydidae	Trachemys callirostris callirostris	Columbian slider	Exotic	Freshwater
Reptiles-Turtles	Emydidae	Trachemys scripta	Pond Slider	Native	Freshwater
Reptiles-Turtles	Emydidae	Trachemys scripta elegans	Red-eared Slider	Native	Freshwater
Reptiles-Turtles	Trionychidae	Apalone ferox	Florida Softshell	Native	Freshwater

Table A.2: Invasive Species in Key Largo, Florida (cont,d)

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